Bρ-defined isochronous mass spectrometry :
a new tool for precision mass measurements of short-lived nuclei

Meng WANG

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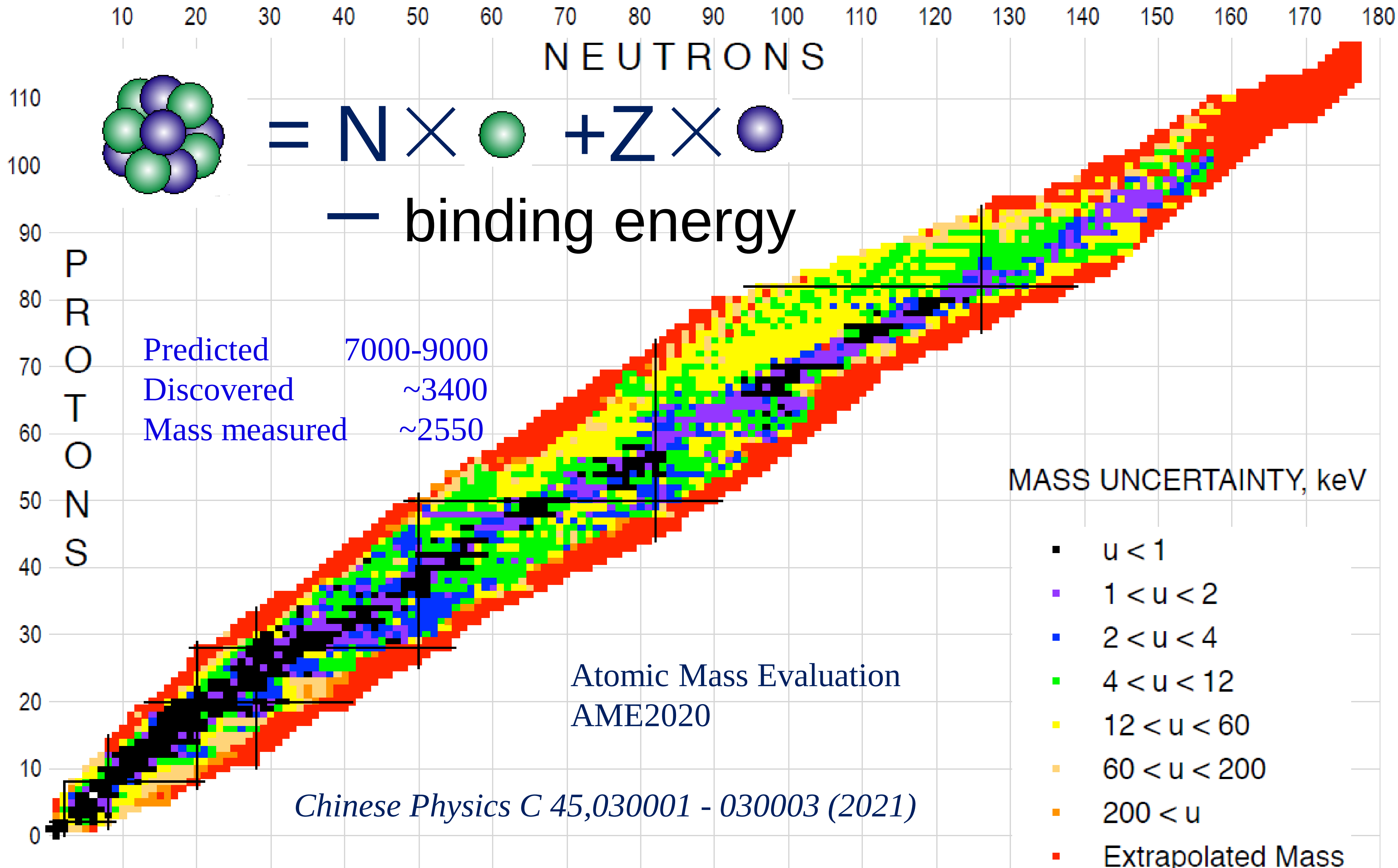
Lanzhou 730000, China

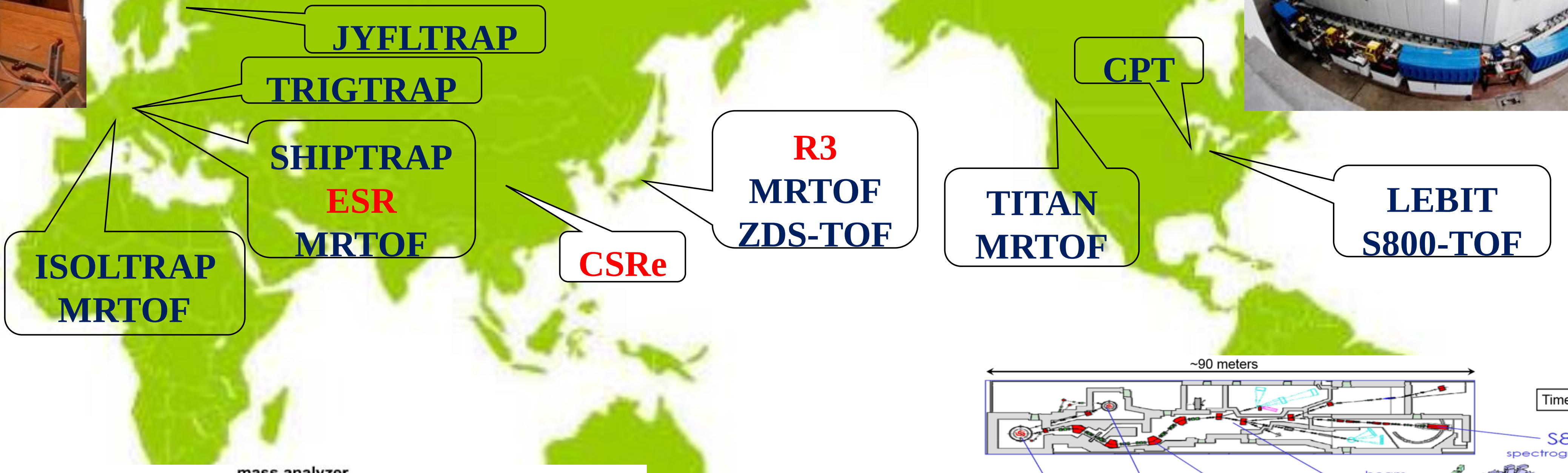
Outline

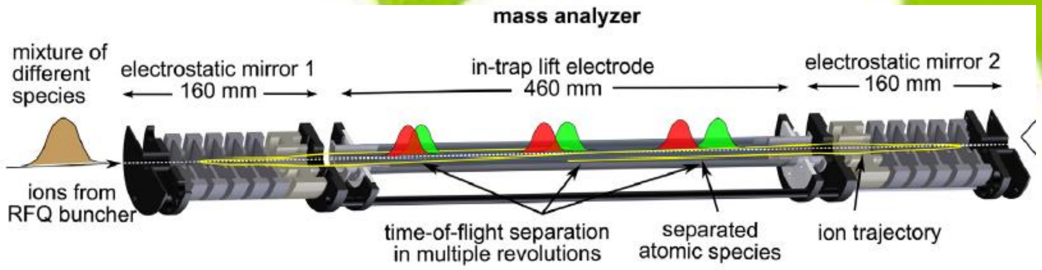


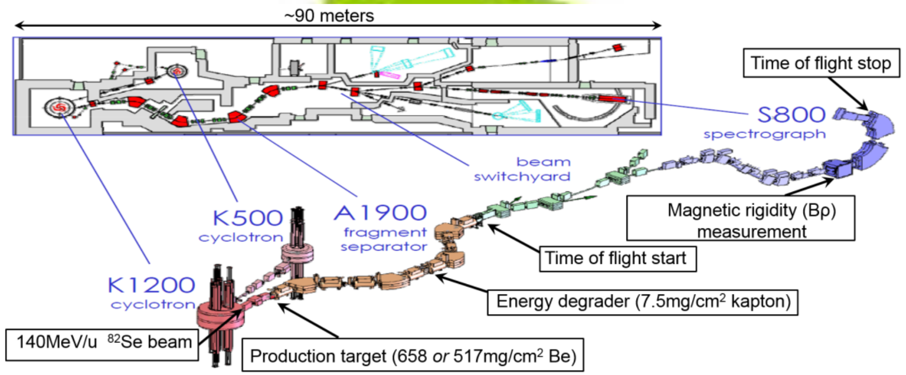
NEUTRONS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
PROTONS
0 10 20 30 40 50 60 70 80 90 100 110
= N × + Z ×
— binding energy
Predicted 7000-9000
Discovered ~3400
Mass measured ~2550
MASS UNCERTAINTY, keV
u < 1
1 < u < 2
2 < u < 4
4 < u < 12
12 < u < 60
60 < u < 200
200 < u
Extrapolated Mass
Atomic Mass Evaluation
AME2020
Chinese Physics C 45,030001 - 030003 (2021)

Nuclear mass measurements

- time： Bρ-TOF, **IMS** < MRTOF < PTMS < SMS
- precision： PTMS > SMS, **IMS**, MRTOF > Bρ-TOF
- many masses simultaneously







Nuclear mass measurements

- time： Bρ-TOF, **IMS** < MRTOF < PTMS < SMS
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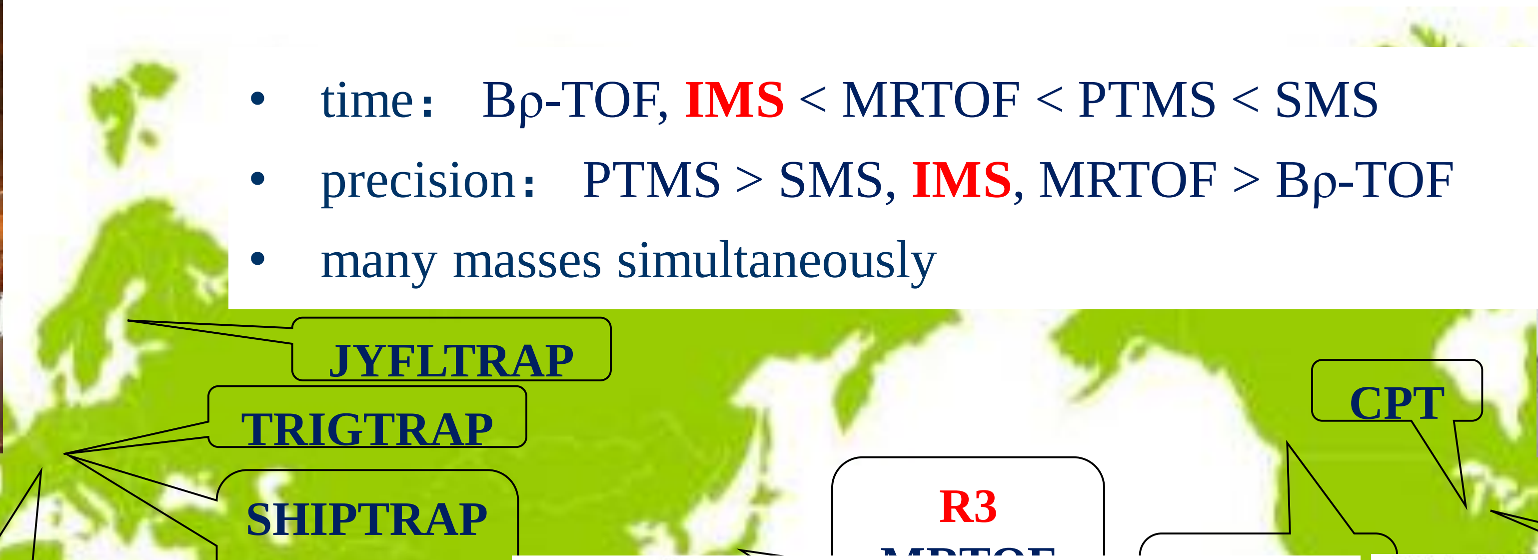
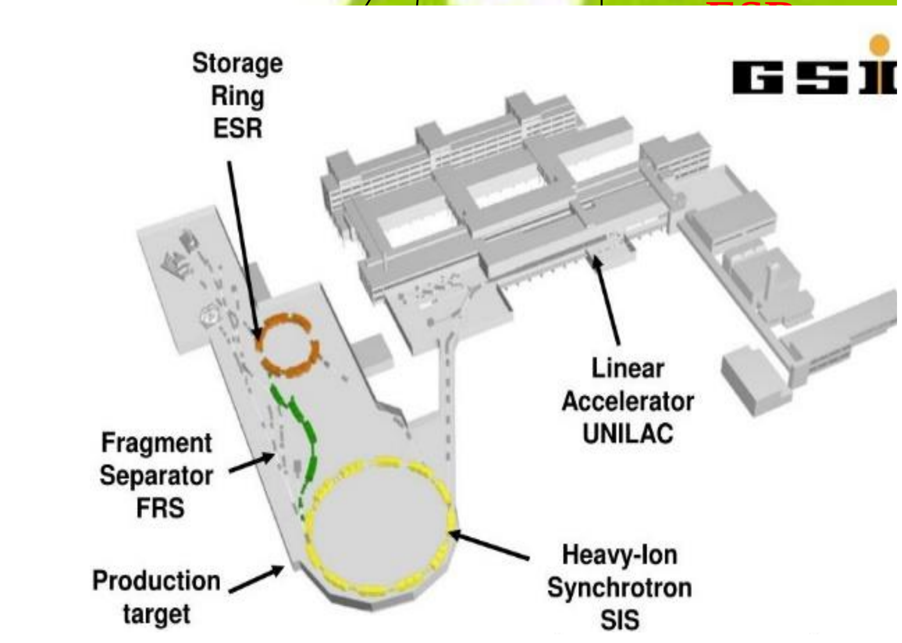
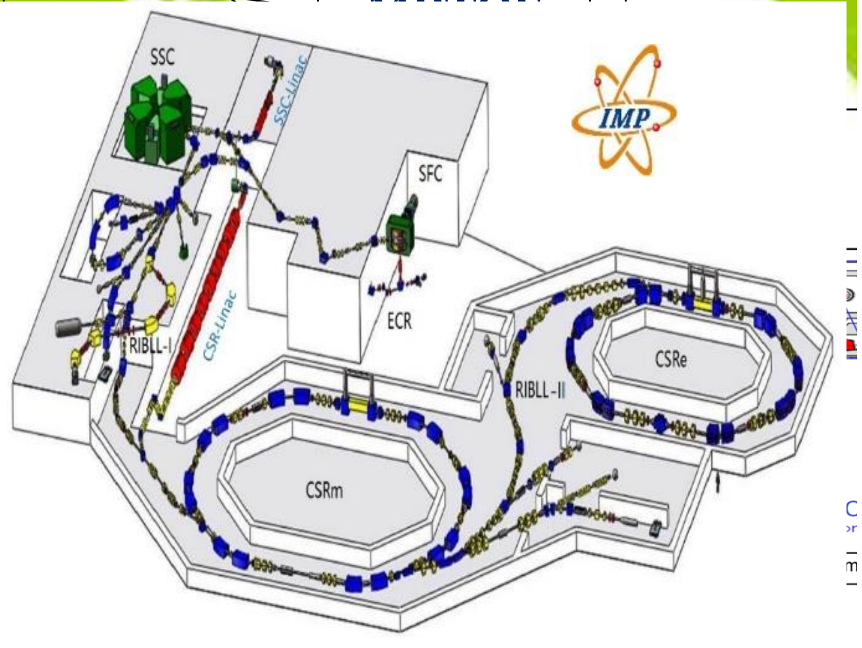
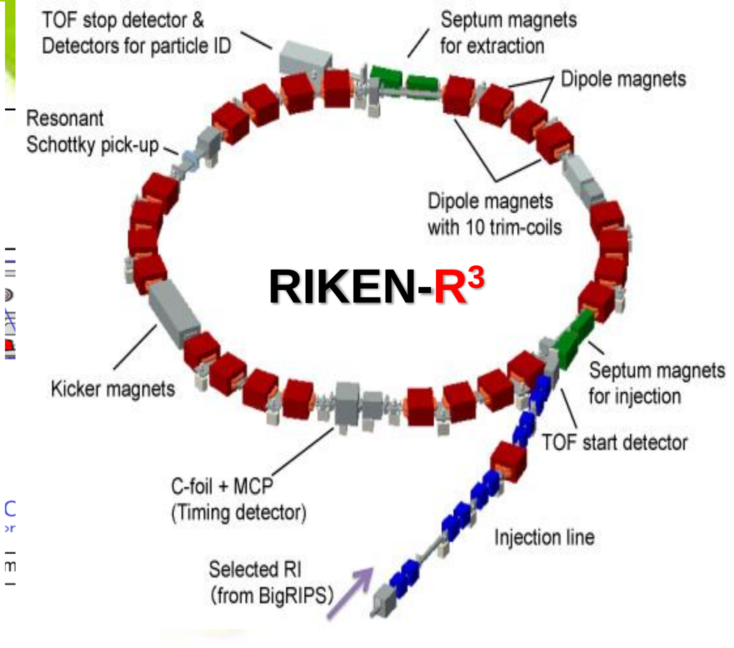
- many masses simultaneously









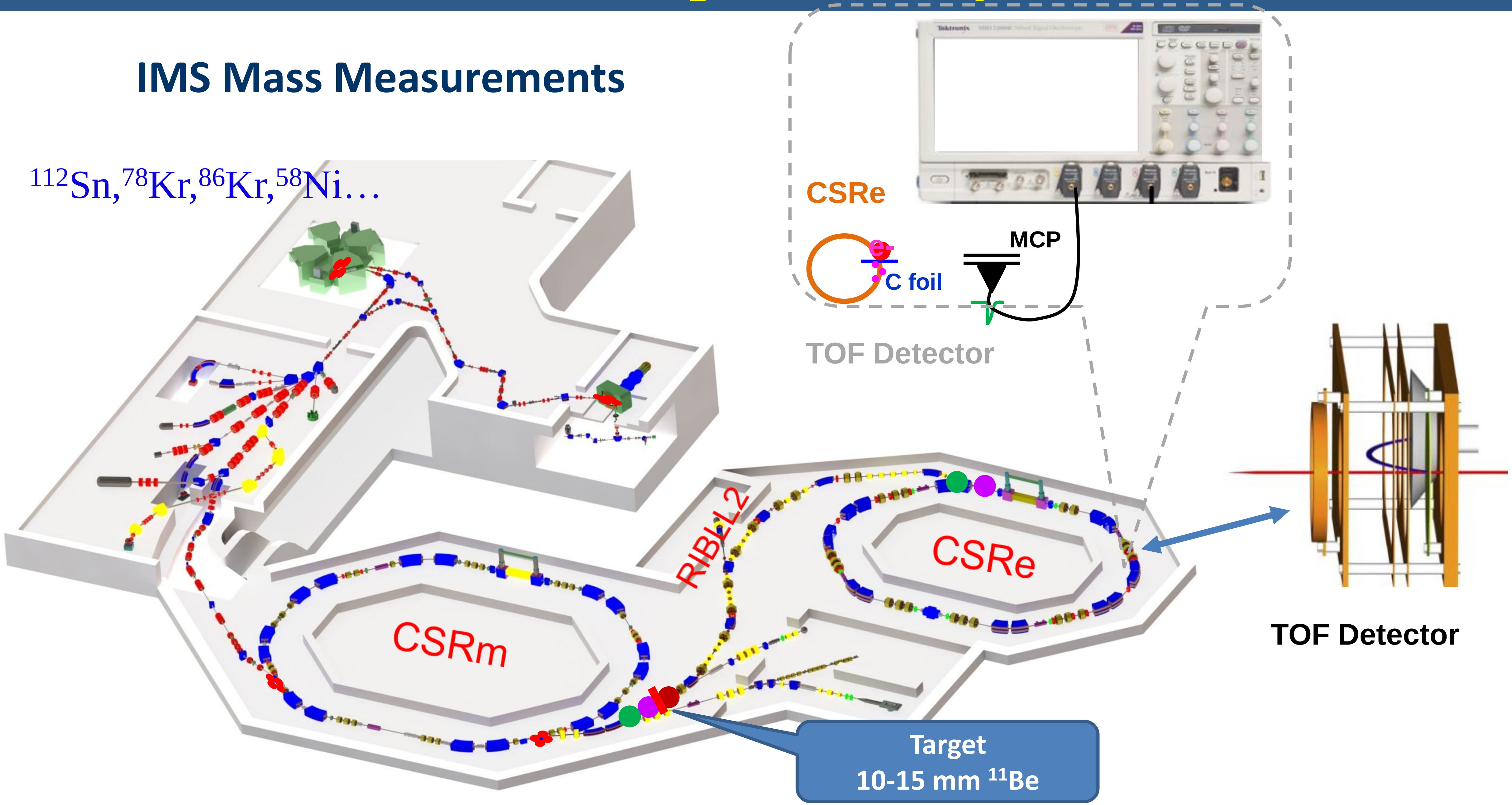
Outline

1. **Why do we measure nuclear masses?**
2. **Isochronous mass spectrometry**
3. **Bρ-defined isochronous mass spectrometry**
4. **New results and perspective**

Isochronous mass spectrometry at CSRe

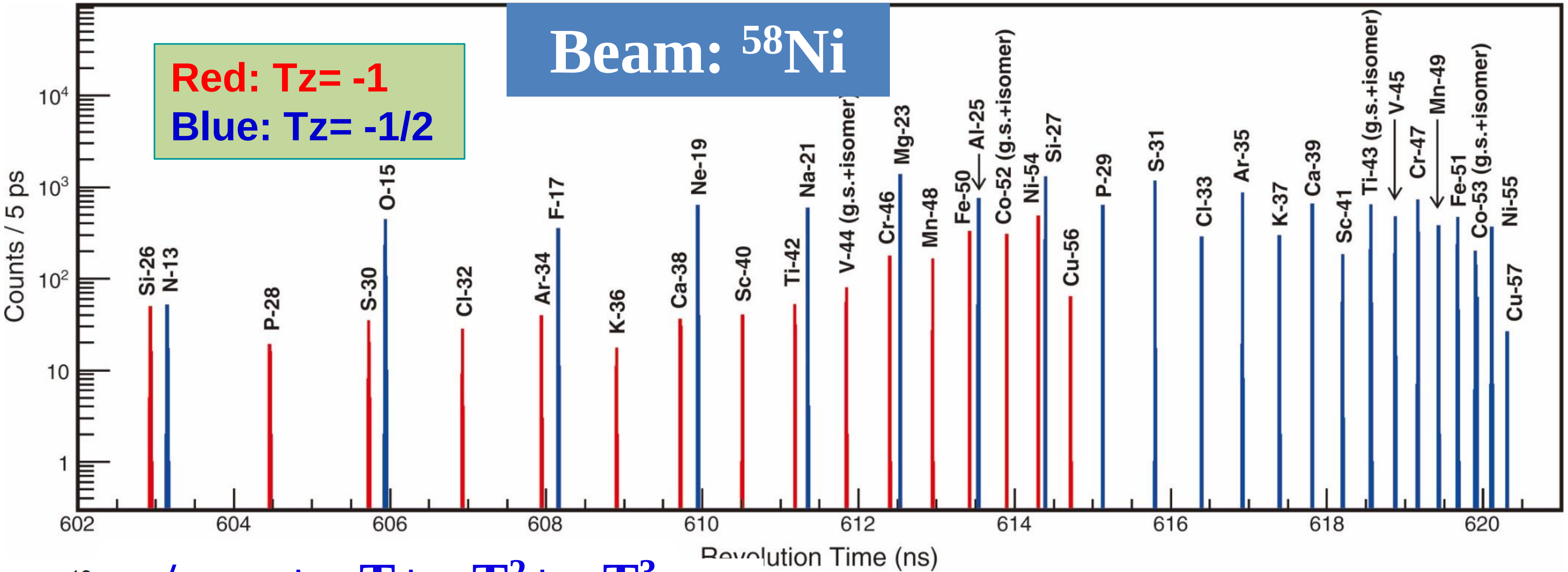
IMS Mass Measurements

^{112}Sn, ^{78}Kr, ^{86}Kr, ^{58}Ni…

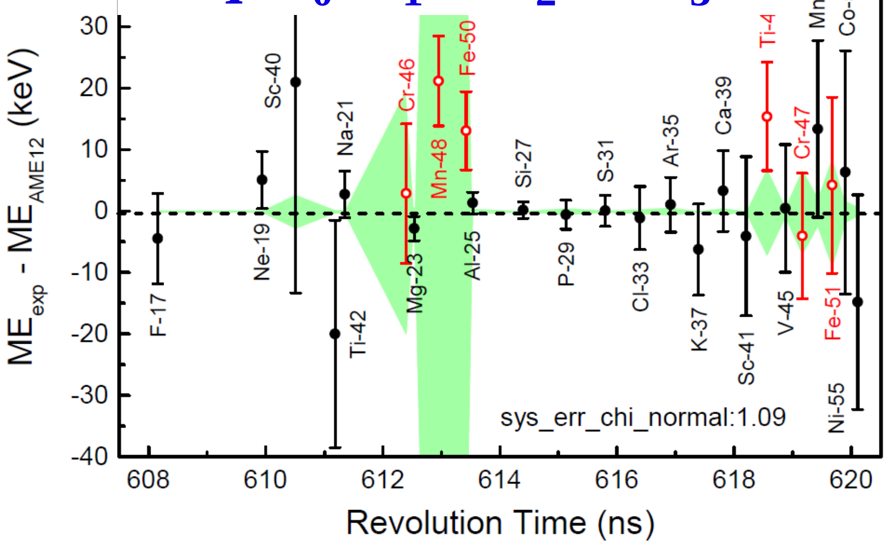


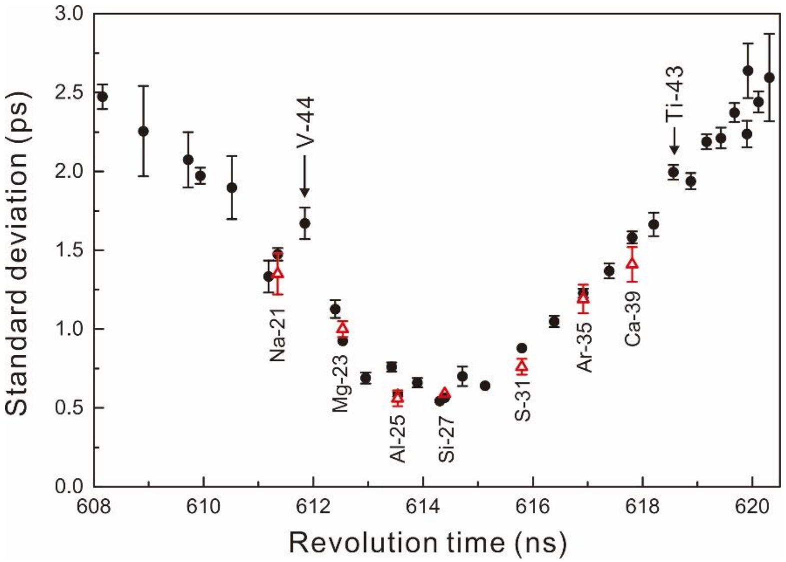
Isochronous mass spectrometry at CSRe

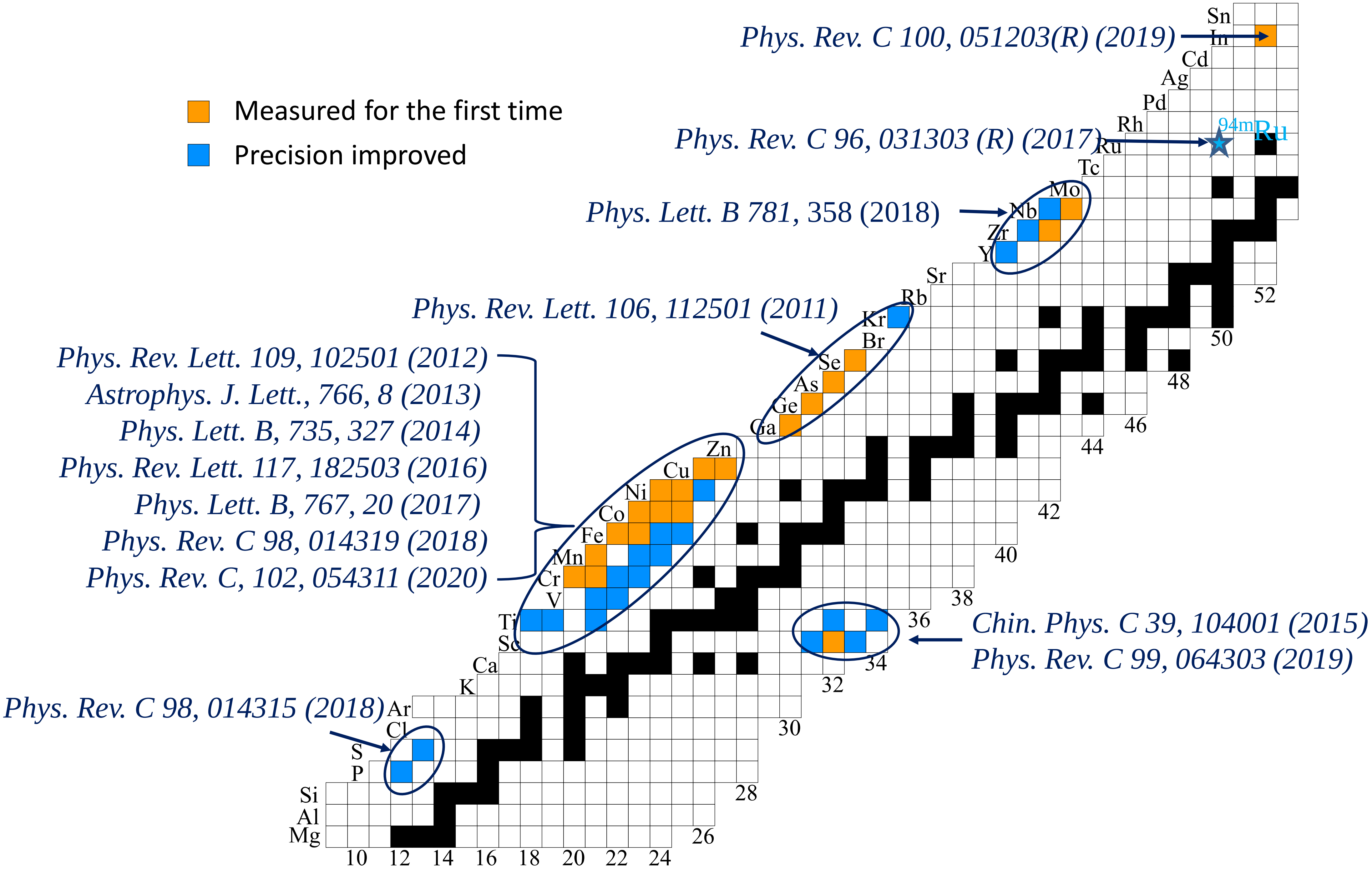
Beam: ^{58}Ni



$$m/q=a_0+a_1T+a_2T^2+a_3T^3$$







Measured for the first time
Precision improved
Phys. Rev. C 100, 051203(R) (2019)
Phys. Rev. C 96, 031303 (R) (2017)
94mRu
Phys. Lett. B 781, 358 (2018)
Phys. Rev. Lett. 106, 112501 (2011)
Phys. Rev. Lett. 109, 102501 (2012)
Astrophys. J. Lett., 766, 8 (2013)
Phys. Lett. B, 735, 327 (2014)
Phys. Rev. Lett. 117, 182503 (2016)
Phys. Lett. B, 767, 20 (2017)
Phys. Rev. C 98, 014319 (2018)
Phys. Rev. C, 102, 054311 (2020)
Chin. Phys. C 39, 104001 (2015)
Phys. Rev. C 99, 064303 (2019)
Phys. Rev. C 98, 014315 (2018)
Sn
In
Cd
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Pd
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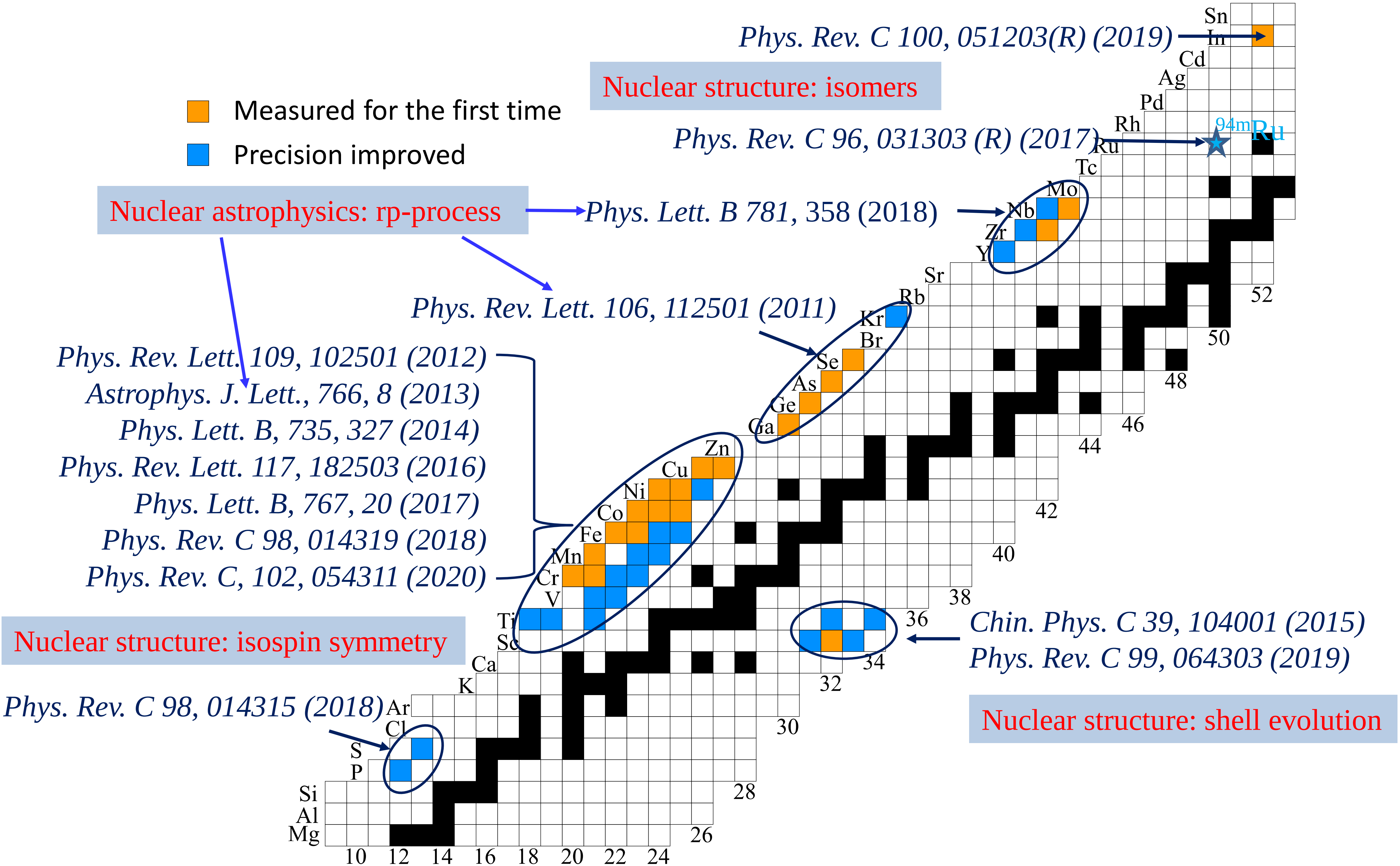

Measured for the first time
Precision improved
Nuclear structure: isomers
Phys. Rev. C 100, 051203(R) (2019)
Phys. Rev. C 96, 031303 (R) (2017)
94mRu
Nuclear astrophysics: rp-process
Phys. Lett. B 781, 358 (2018)
Phys. Rev. Lett. 106, 112501 (2011)
Phys. Rev. Lett. 109, 102501 (2012)
Astrophys. J. Lett., 766, 8 (2013)
Phys. Lett. B, 735, 327 (2014)
Phys. Rev. Lett. 117, 182503 (2016)
Phys. Lett. B, 767, 20 (2017)
Phys. Rev. C 98, 014319 (2018)
Phys. Rev. C, 102, 054311 (2020)
Nuclear structure: isospin symmetry
Phys. Rev. C 98, 014315 (2018)
Chin. Phys. C 39, 104001 (2015)
Phys. Rev. C 99, 064303 (2019)
Nuclear structure: shell evolution
Sn
In
Cd
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Ni
Co
Fe
Mn
Cr
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Ca
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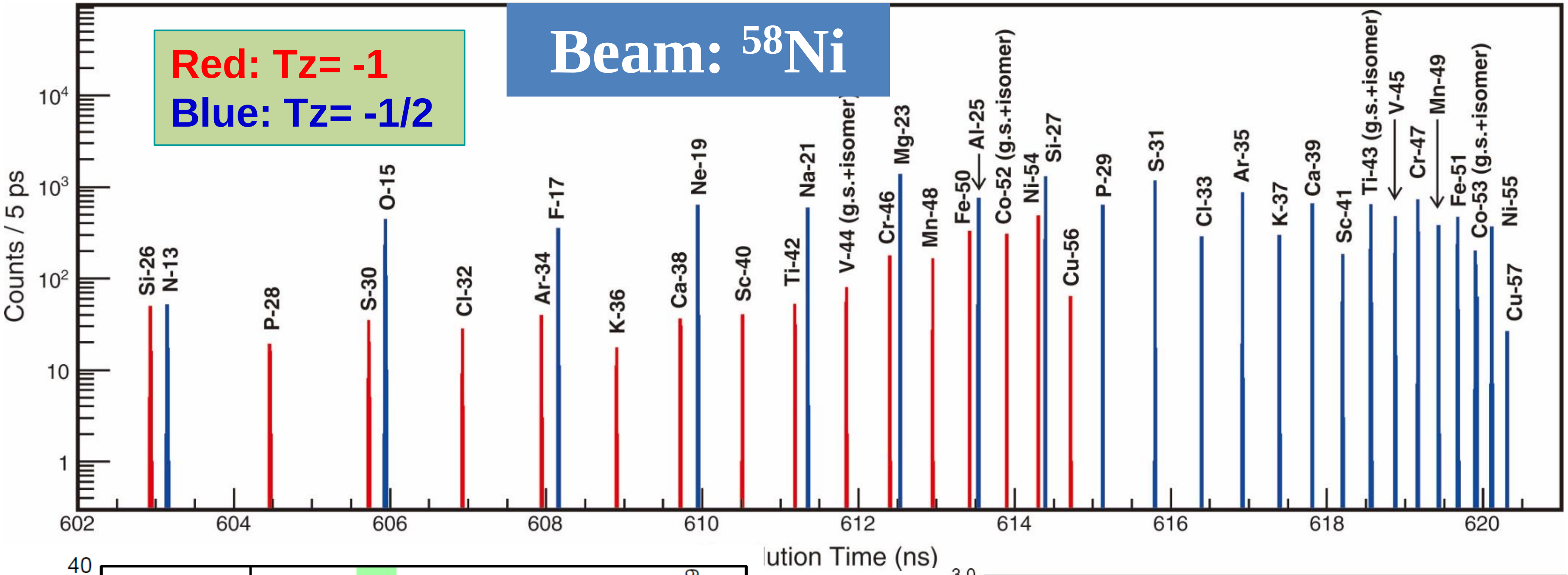
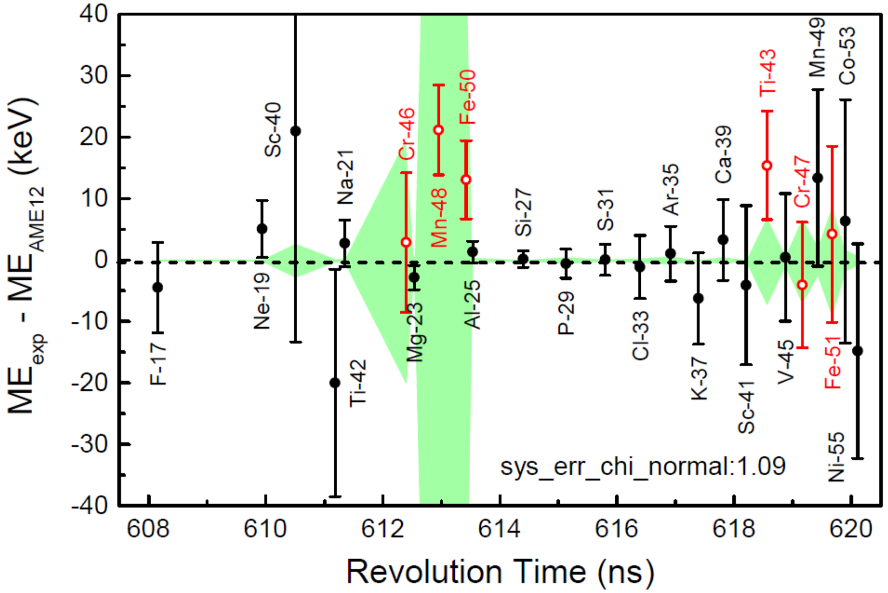
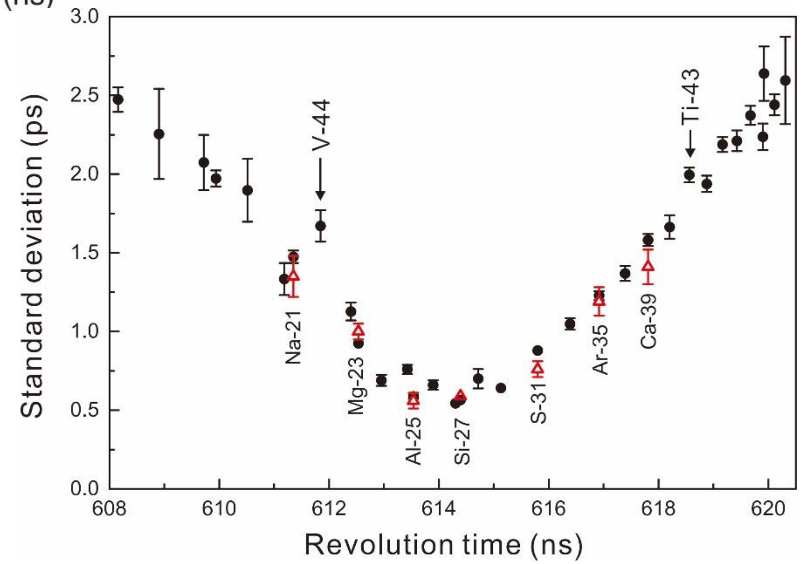
Isochronous mass spectrometry at CSRe

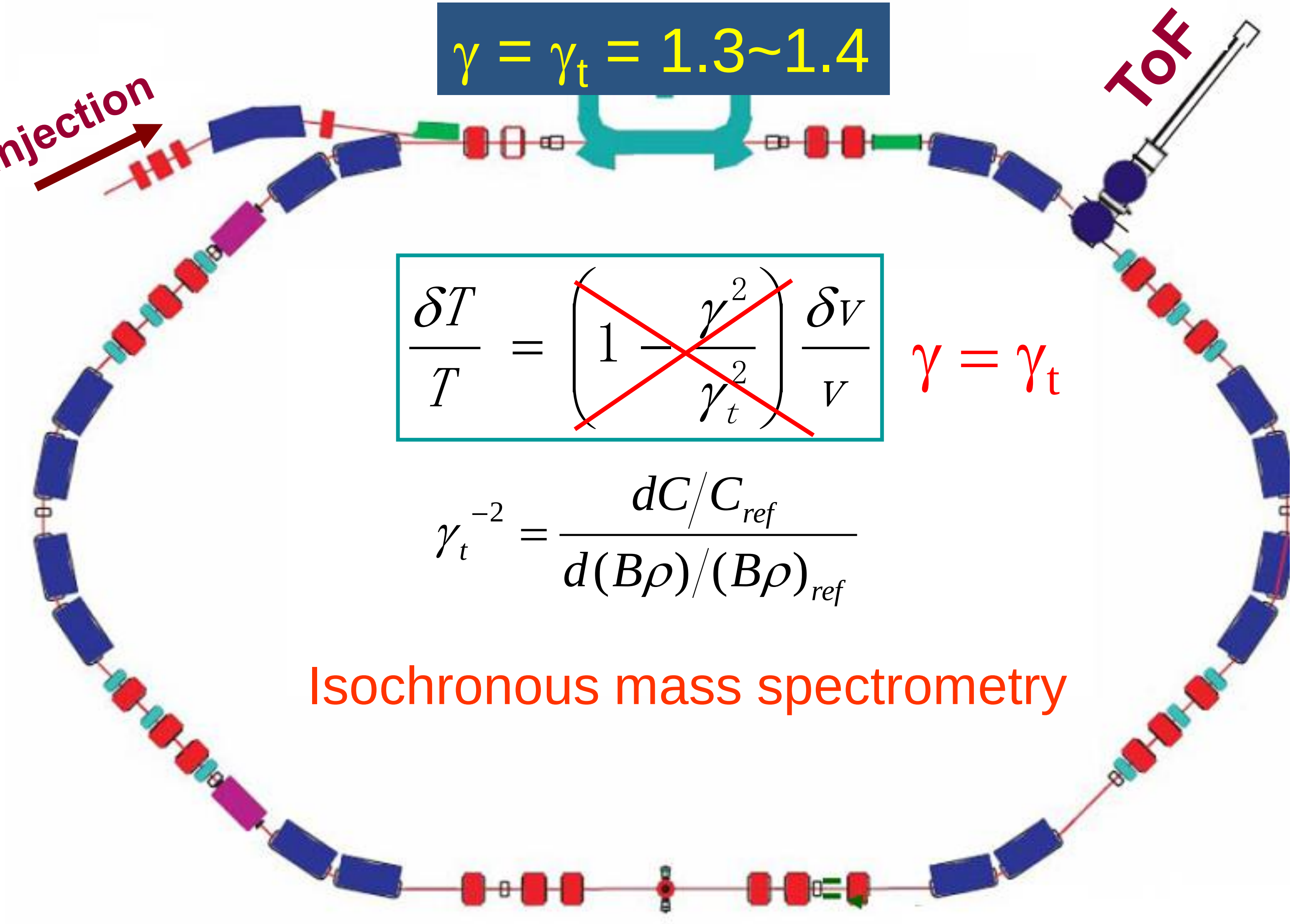






Isochronous mass spectrometry at CSRe

$\gamma = \gamma_t = 1.3\sim1.4$



$$\frac{\delta T}{T} = \left(\cancel{1-\frac{\gamma^2}{\gamma_t^2}}\right)\frac{\delta v}{v}$$

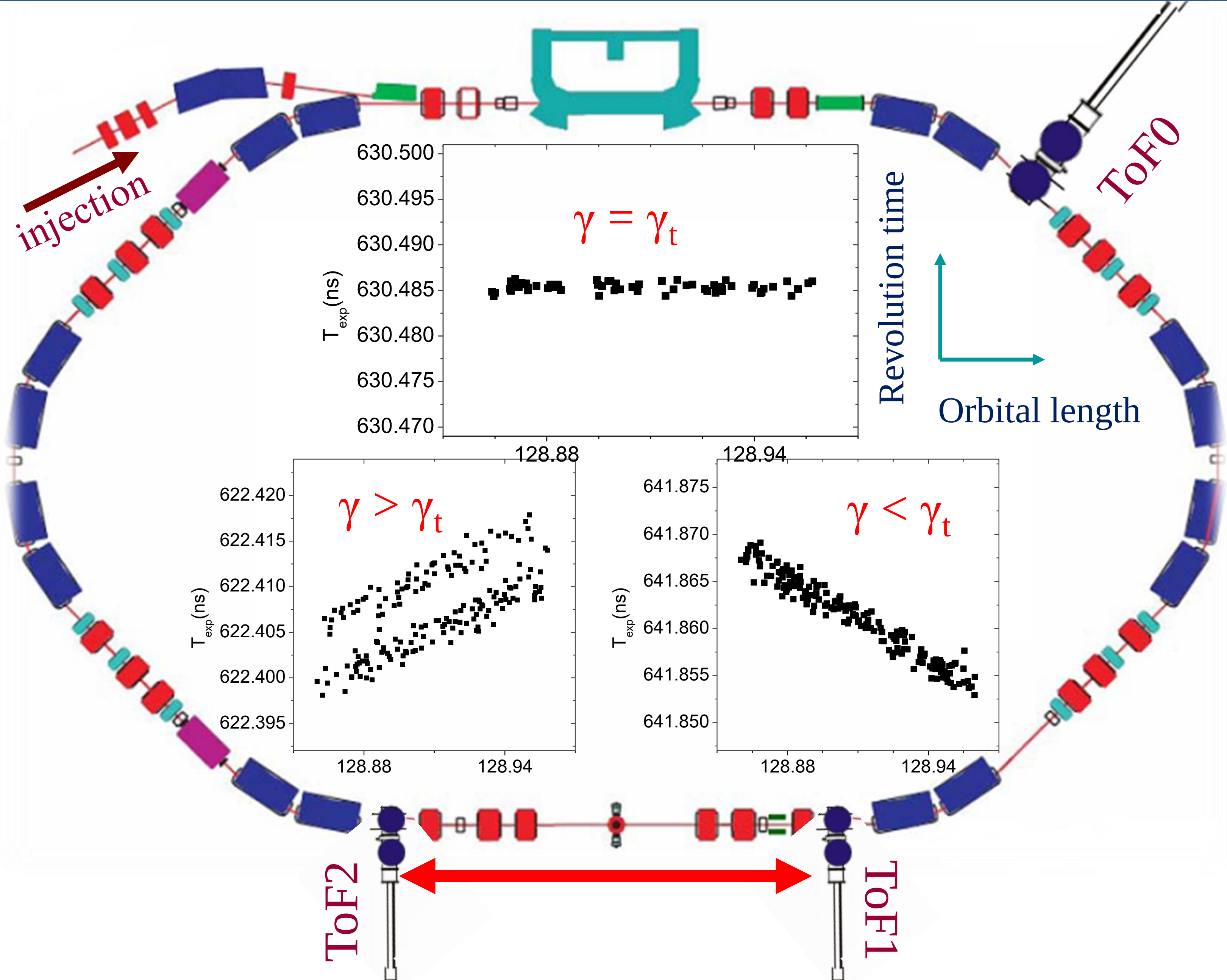
$\gamma = \gamma_t$

$$\gamma_t^{-2} = \frac{dC/C_{ref}}{d(B\rho)/(B\rho)_{ref}}$$

Isochronous mass spectrometry

X. L. Tu et al., NIM A 654, 213 (2011)

Isochronous mass spectrometry at CSRe



Outline

1. **Why do we measure nuclear masses?**
2. **Isochronous mass spectrometry**
3. **Bρ-defined isochronous mass spectrometry**
4. **New results and perspective**

New scheme for mass measurements

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) S1779–S1783 doi:10.1088/0954-3899/31/10/072

Precision experiments with relativistic exotic nuclei at GSI

H Geissel[1,2] and Yu A Litvinov[1,2]

the narrow range where the isochronous conditions are fulfilled. The analysis with only one time-of-flight (ToF) detector positioned inside the ESR lattice [26] requires, in principle, a strong restriction on the accepted mass-to-charge ratio. A solution is to measure the velocity of each fragment in addition to the revolution time. This will provide a correlation to account for the deviations from the strict isochronous condition. For this purpose, additional detectors could be placed within the FRS, inside the ESR, and behind the extraction channel from the ESR. Within the FRS both magnetic rigidity and time-of-flight measurements are possible. However, a restriction is certainly the higher particle rate compared to the actually stored ions in the ESR. The advantage with a second ToF detector within the ESR is the turn-by-turn velocity correlation measurement. The velocity measurement of the extracted beam after many revolutions in the ESR also has advantages. For example, the velocity can be measured

New scheme for mass measurements

NIM A 756 (2014) 1

Installation of two TOFs

2013

2014

First online test

Chin. Phy. C 39 (2015) 106201
Phys. Scr. T166 (2015) 014010

NIM A 898 (2018) 111

Optimizations of the optical settings

2015

2016

2017

Laser calibration system

NIM A 931 (2019) 52

Phys. Rev. Accel. Beams 24 (2021) 042802
NIM A 1027 (2022) 166329

First physics experiment
^{58}Ni beam

2018

2019

^{86}Kr beam

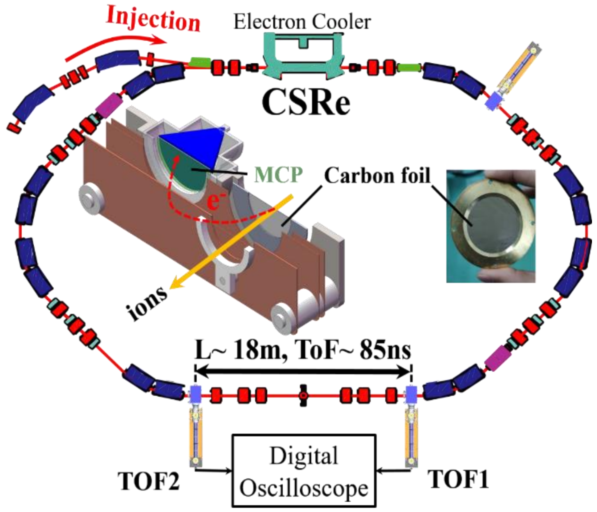
2020

Fist new masses
^{78}Kr beam

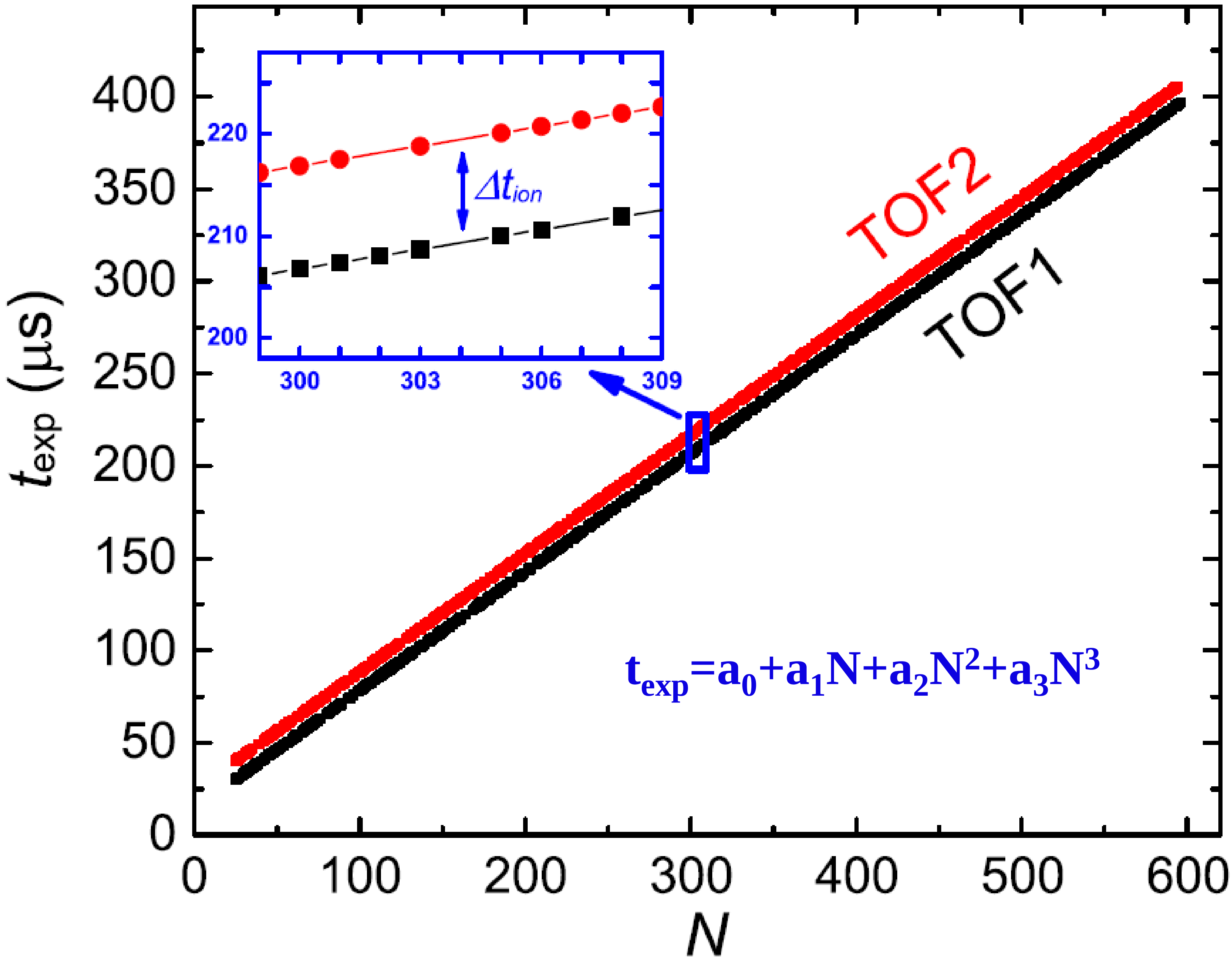
2021年

^{36}Ar beam

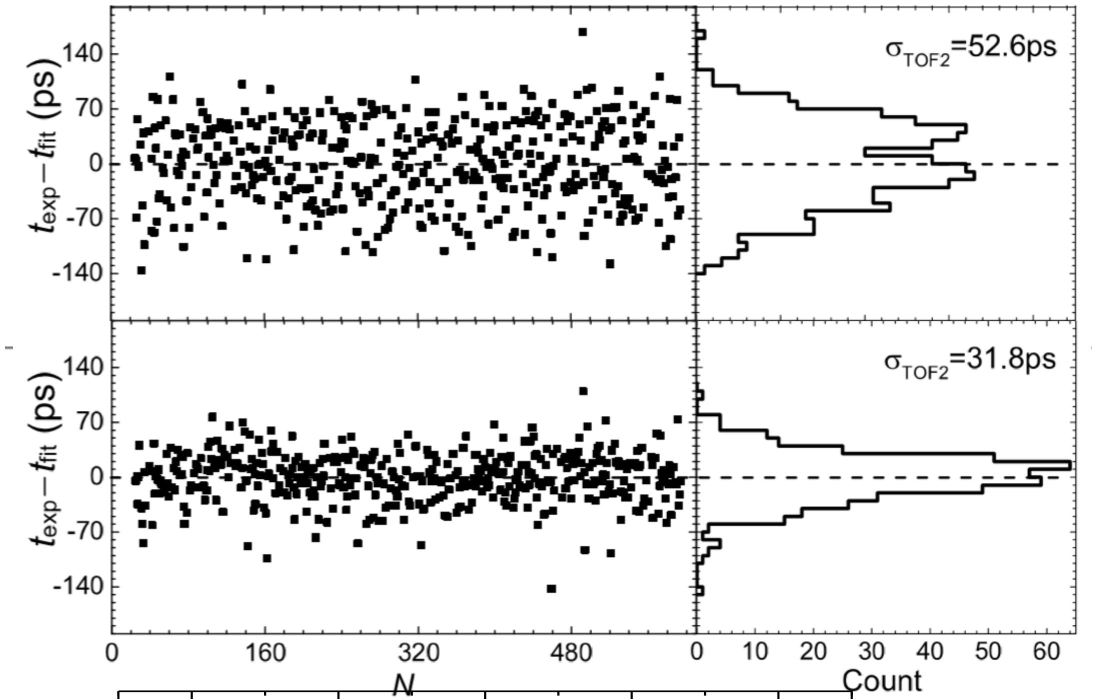
Precision velocity measurement, accurate calibration, correction for the fluctuations of magnetic fields……

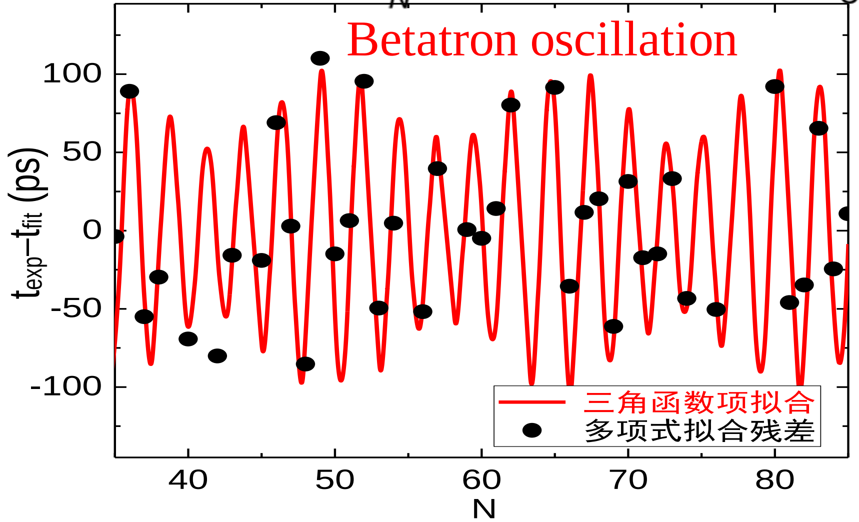


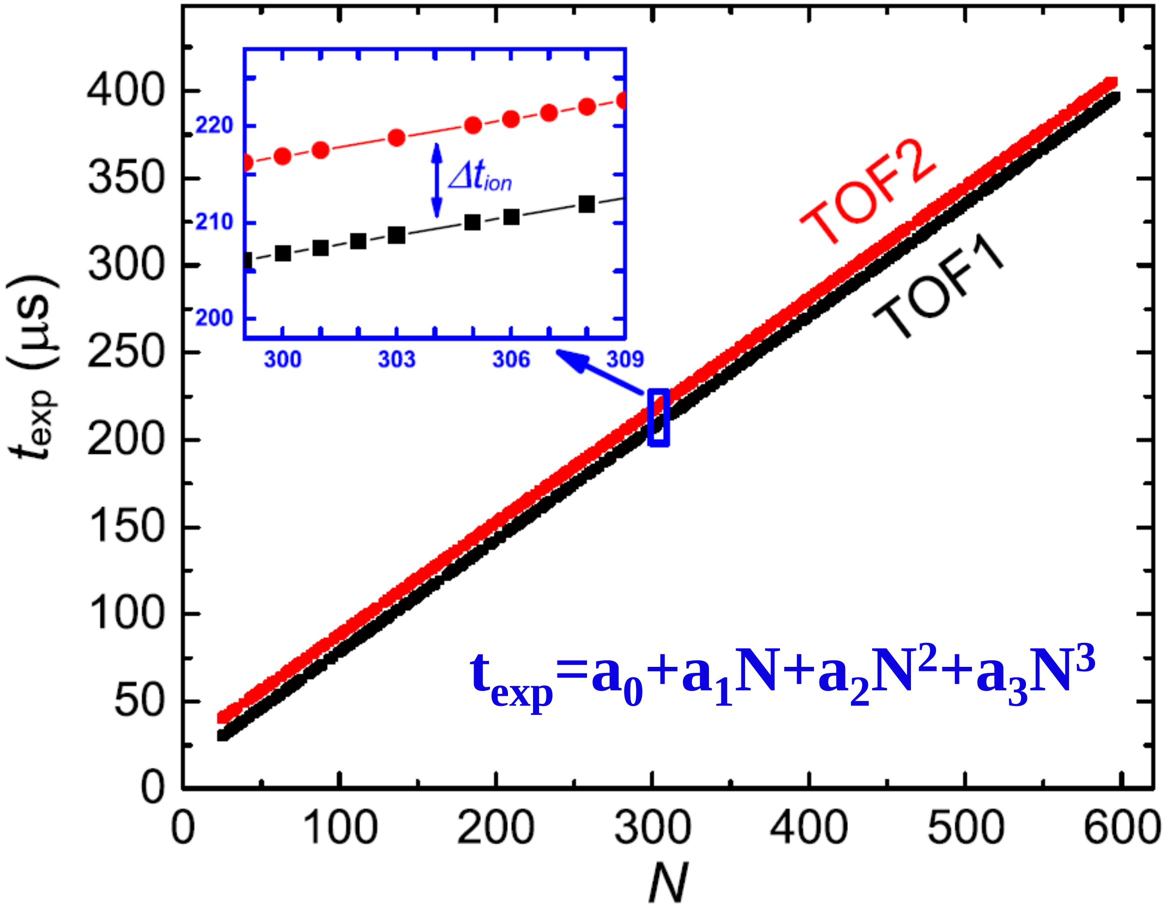
Bρ-defined isochronous mass spectrometry



Bρ-defined isochronous mass spectrometry

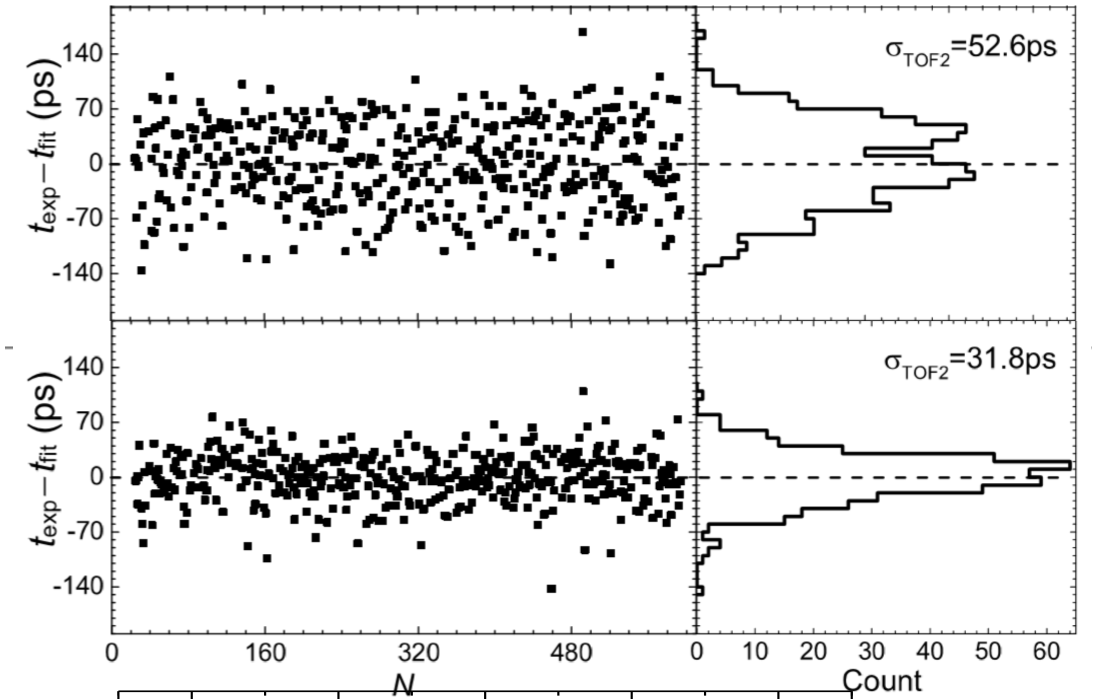


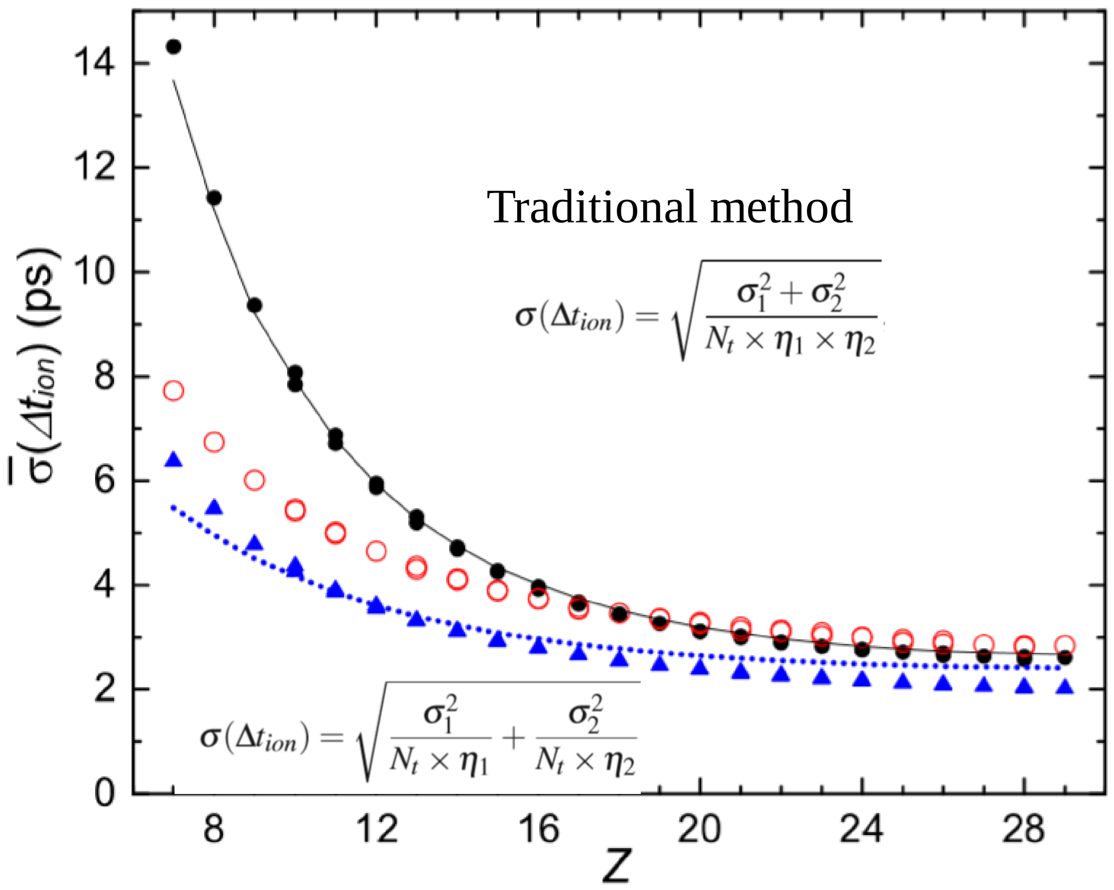


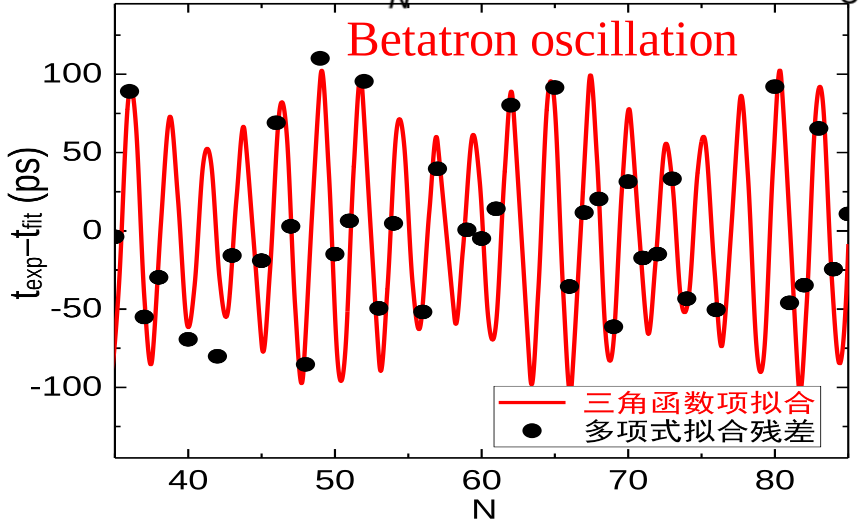


- Precision in-ring velocity measurement
- Impact of the Betatron oscillation

Bρ-defined isochronous mass spectrometry







- Precision in-ring velocity measurement
- Impact of the Betatron oscillation

Bρ-defined isochronous mass spectrometry

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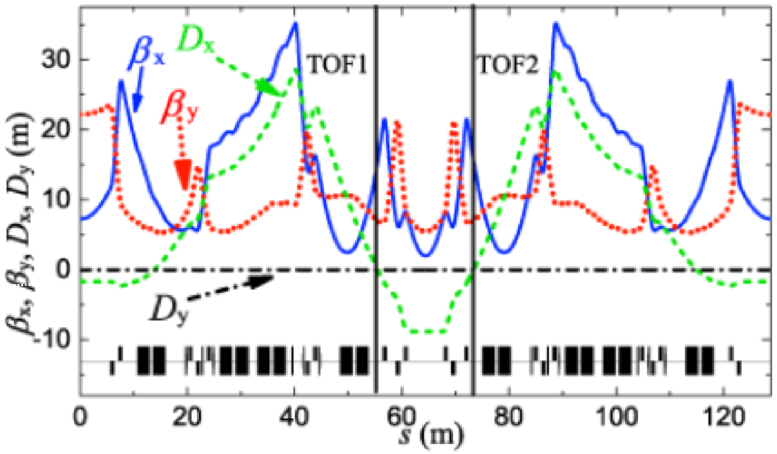
In-ring velocity measurement for isochronous mass spectrometry

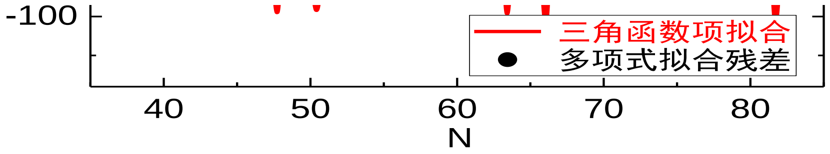
X. Zhou *et al.*

Phys. Rev. Accel. Beams **24**, 042802 (2021)



Detecting the time difference between traversals of two thin foils, 18 m apart, allows measuring the velocity of short-lived nuclei, circulating in a storage ring over a few hundred turns, with a relative precision of 10 ppm.

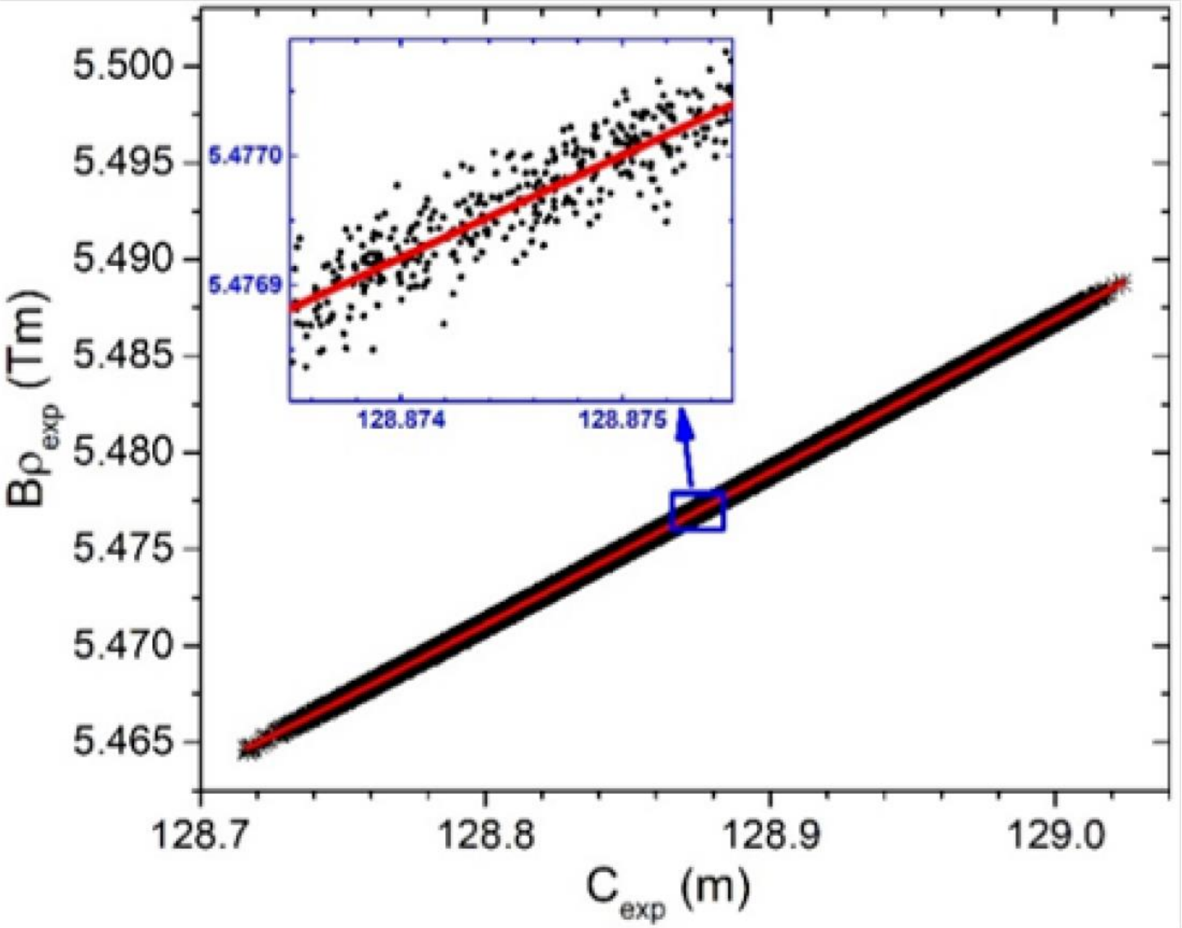
$$v = \frac{L}{\Delta t_{\mathrm{TOF}}} = \frac{L}{\Delta t_{\mathrm{exp}} - \Delta t_{\mathrm{d}}}$$

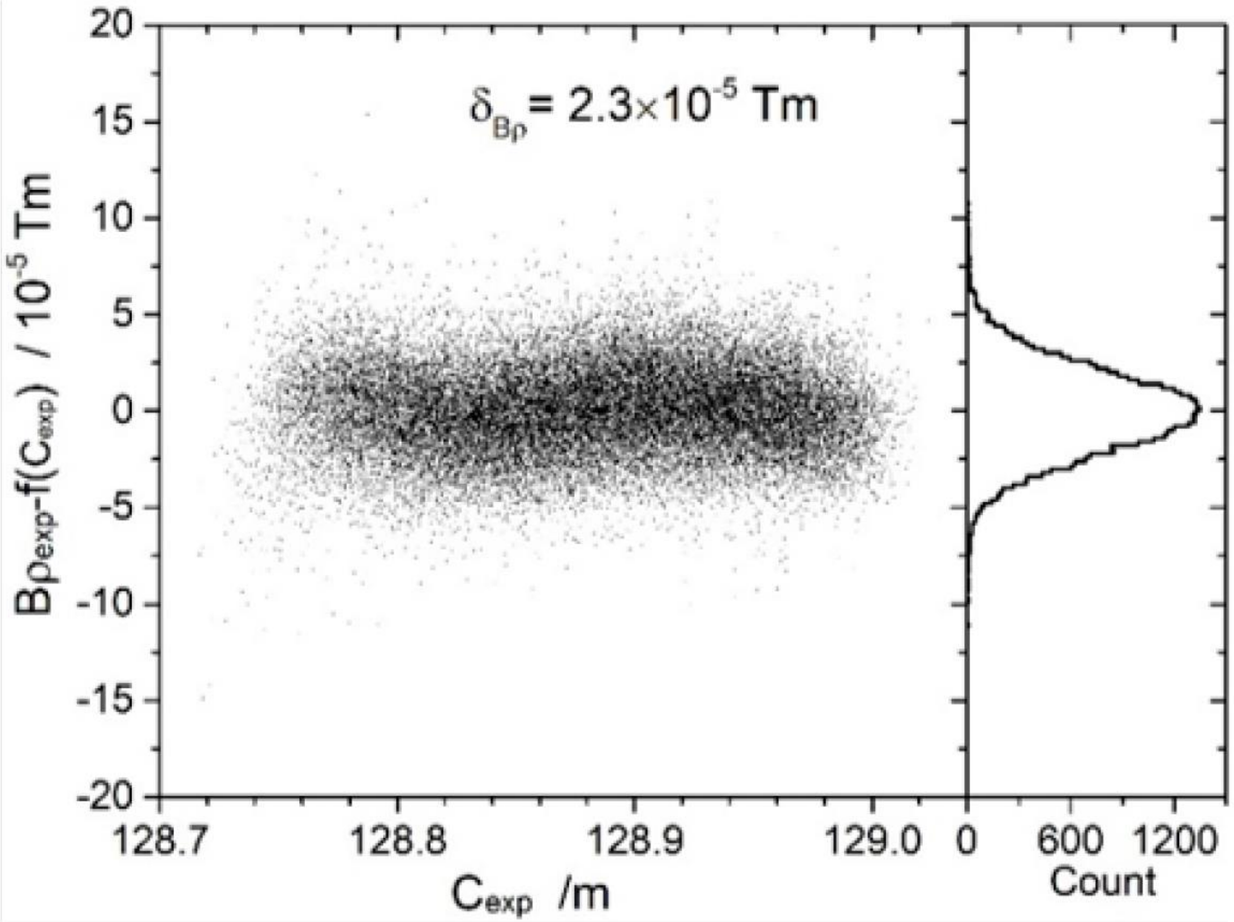


- Impact of the Betatron oscillation

Bρ-defined isochronous mass spectrometry

$$B\rho = \frac{m}{q}\gamma v, \qquad T = \frac{C}{v}$$





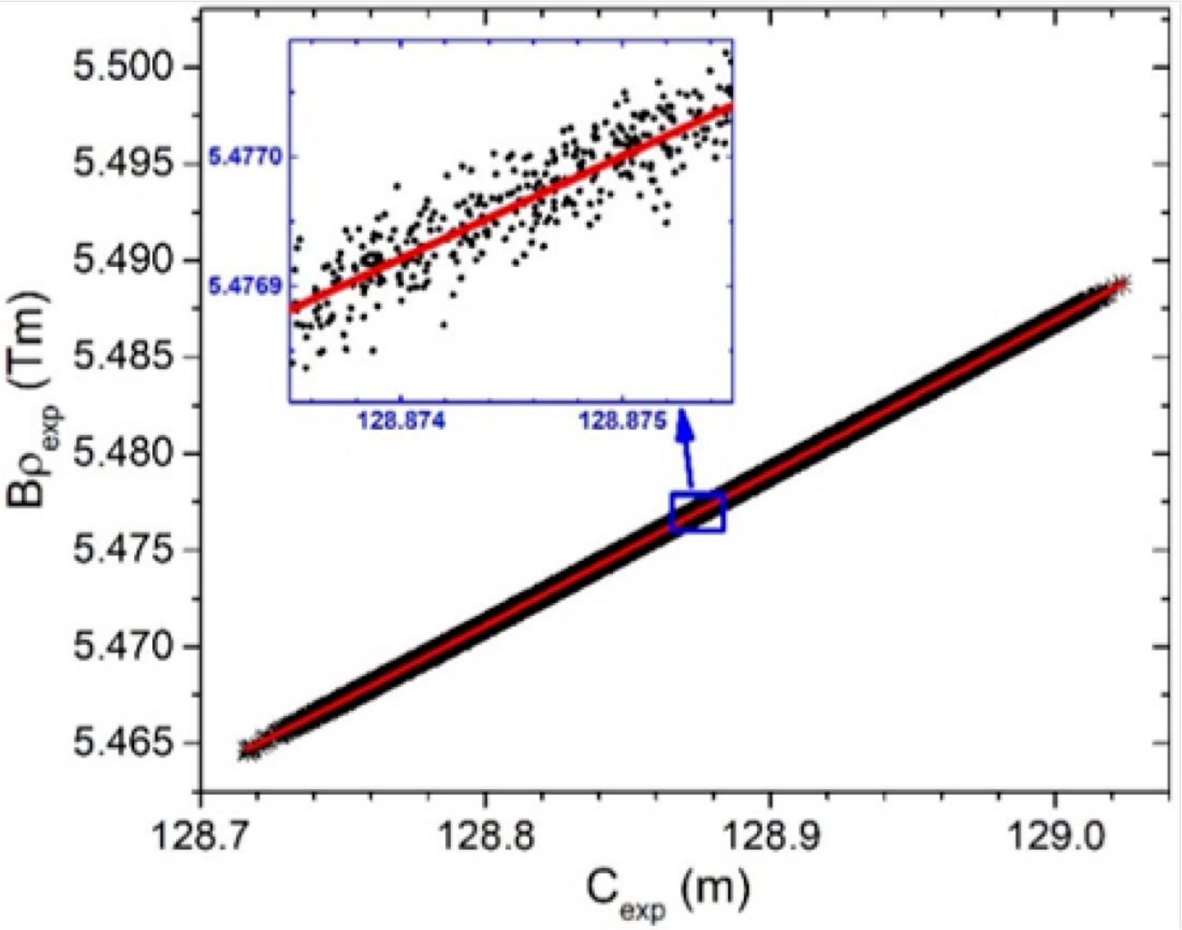
$$\frac{1}{\gamma_t^2} = \frac{\Delta C/C}{\Delta B\rho/B\rho} \qquad B\rho = f(C) = (B\rho)_0\left(\frac{C}{C_0}\right)^{\gamma_t^2}$$

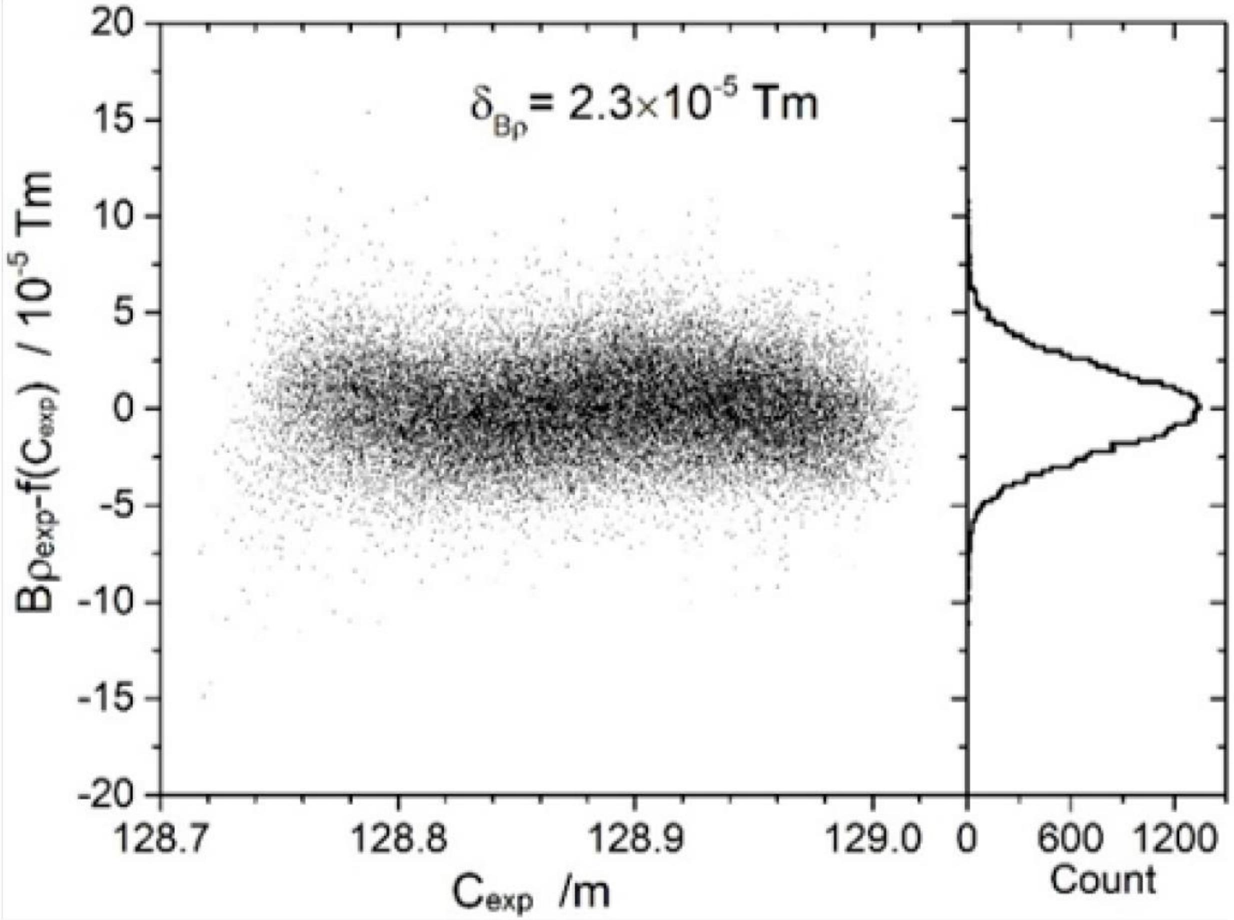
$$B\rho = f(C) = (B\rho)_0\left(\frac{C}{C_0}\right)^{K} + a_1 e^{-a_2(C-C_0)}$$

Bρ-defined isochronous mass spectrometry

$$B\rho = \frac{m}{q}\gamma v, \qquad T = \frac{C}{v}$$

$$\left(\frac{m}{q}\right)_i = \frac{f(C^i_{\exp})}{(\gamma v)^i} \qquad i = 1,\ 2,\ 3, \ldots,$$

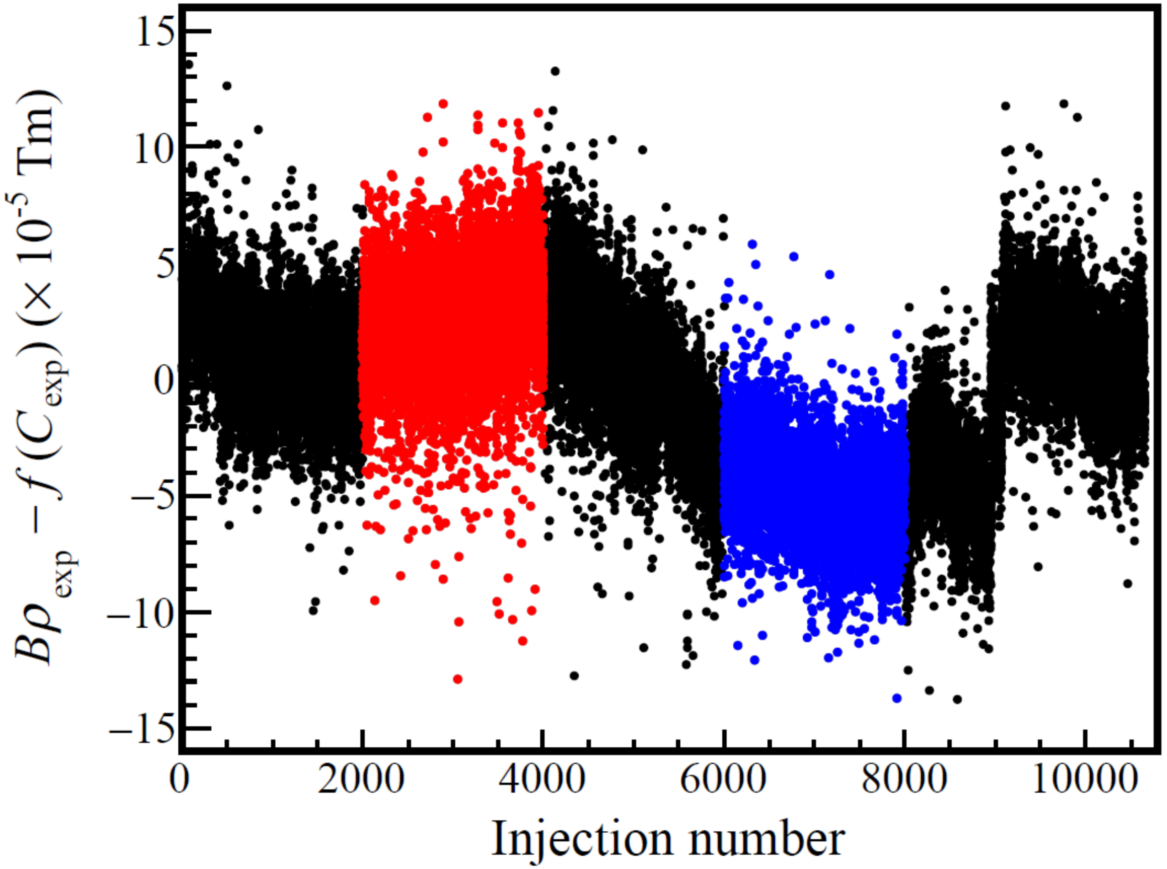


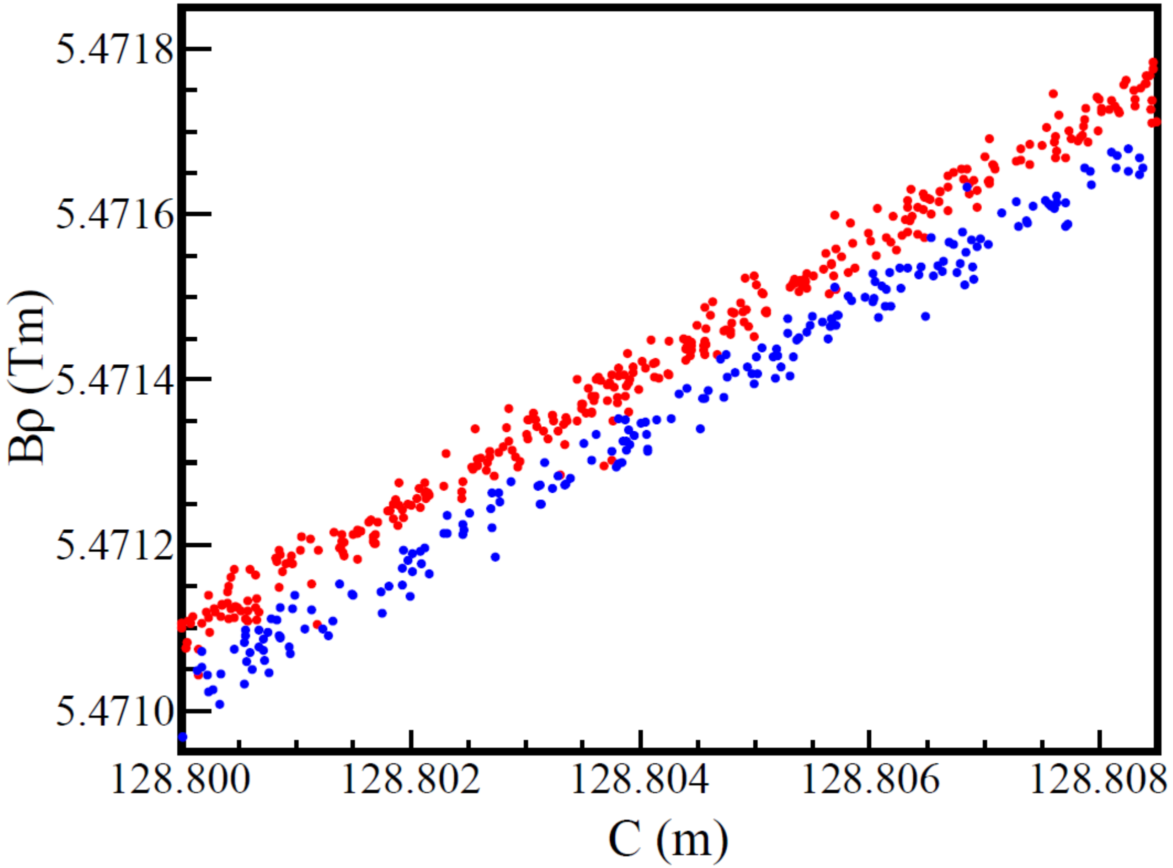


$$\frac{1}{\gamma_t^2} = \frac{\Delta C/C}{\Delta B\rho/B\rho} \qquad B\rho = f(C) = (B\rho)_0\left(\frac{C}{C_0}\right)^{\gamma_t^2}$$

$$B\rho = f(C) = (B\rho)_0\left(\frac{C}{C_0}\right)^{K} + a_1 e^{-a_2(C-C_0)}$$

Bρ-defined isochronous mass spectrometry

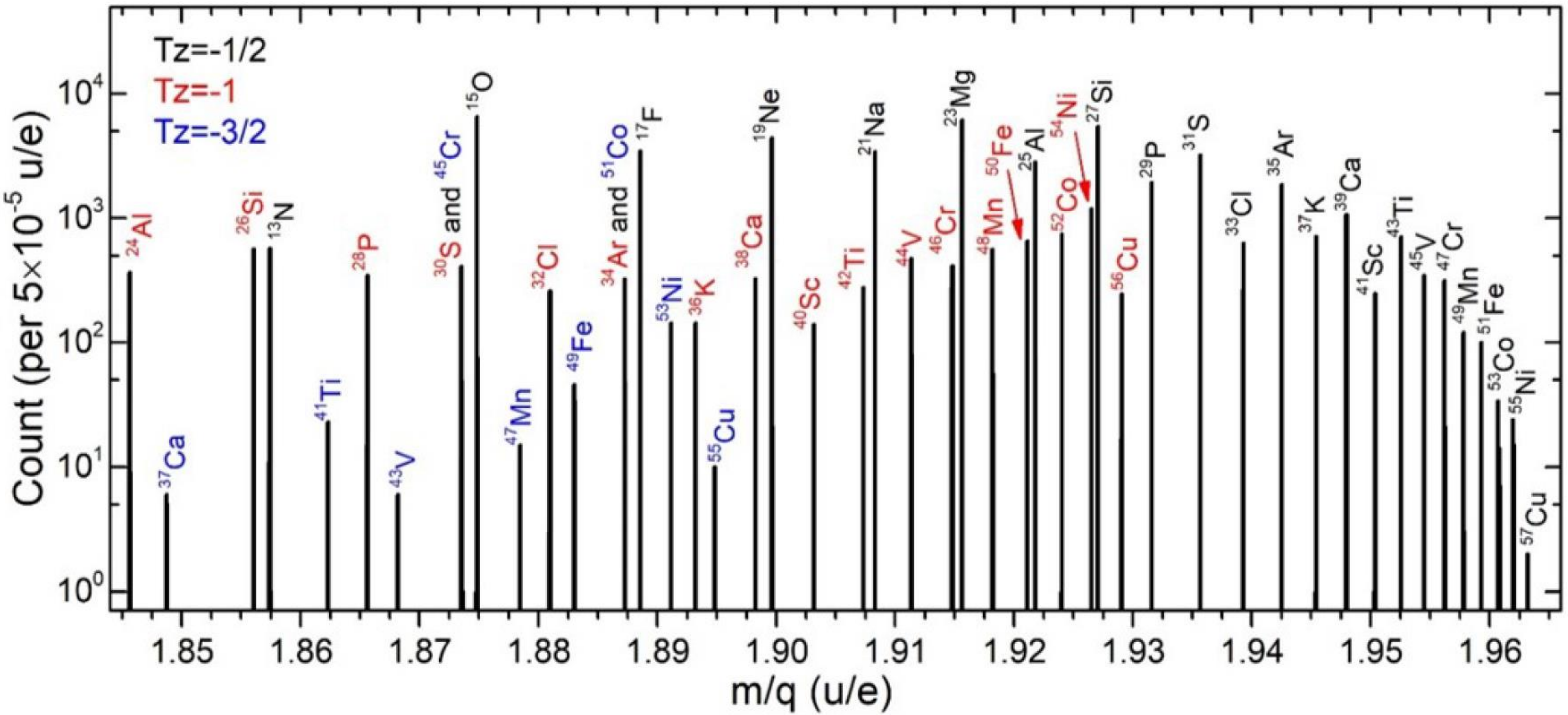




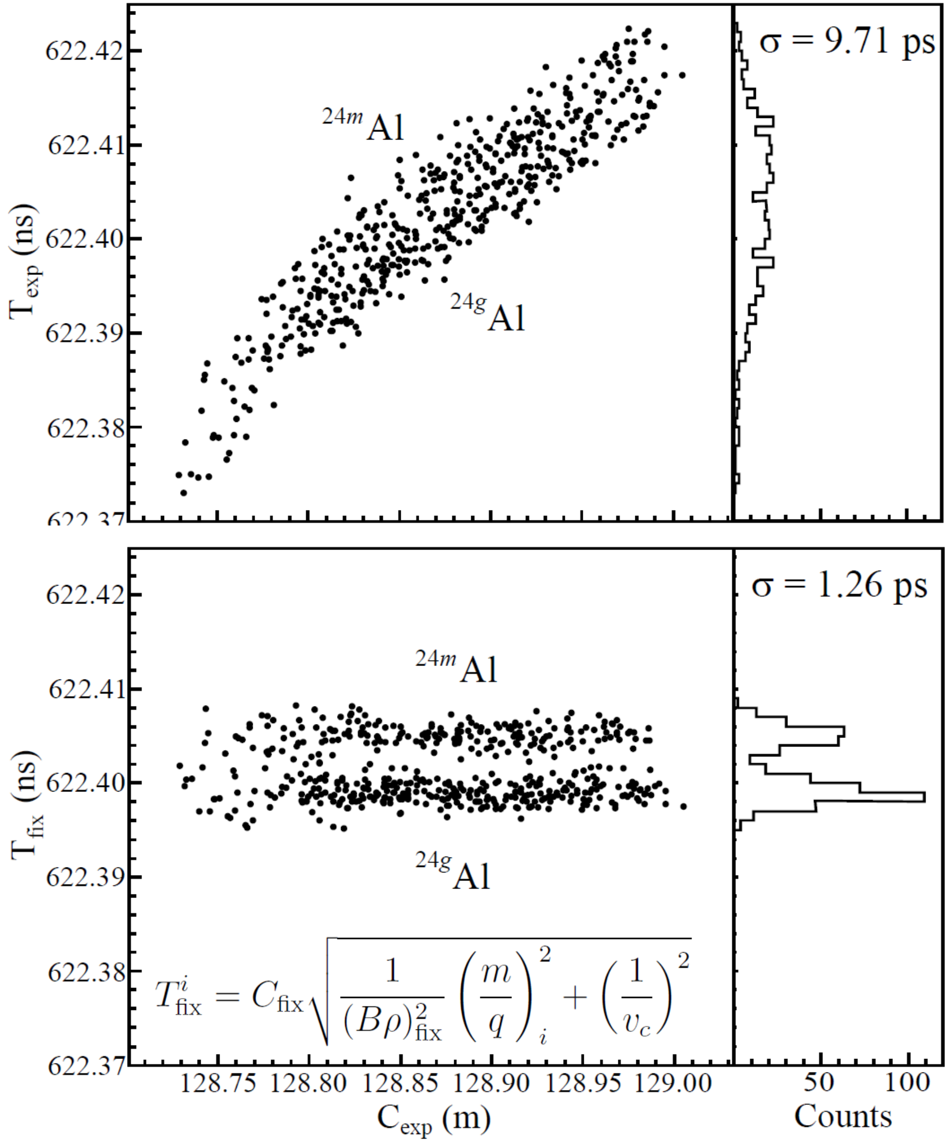
$$M = \overline{\left[\frac{(B\rho)_{\mathrm{exp}}}{f(C)}\right]} = \frac{\sum_i^{N_p} w_i \left[\frac{(B\rho)^i_{\mathrm{exp}}}{f(C^i_{\mathrm{exp}})}\right]}{\sum_i^{N_p} w_i},$$

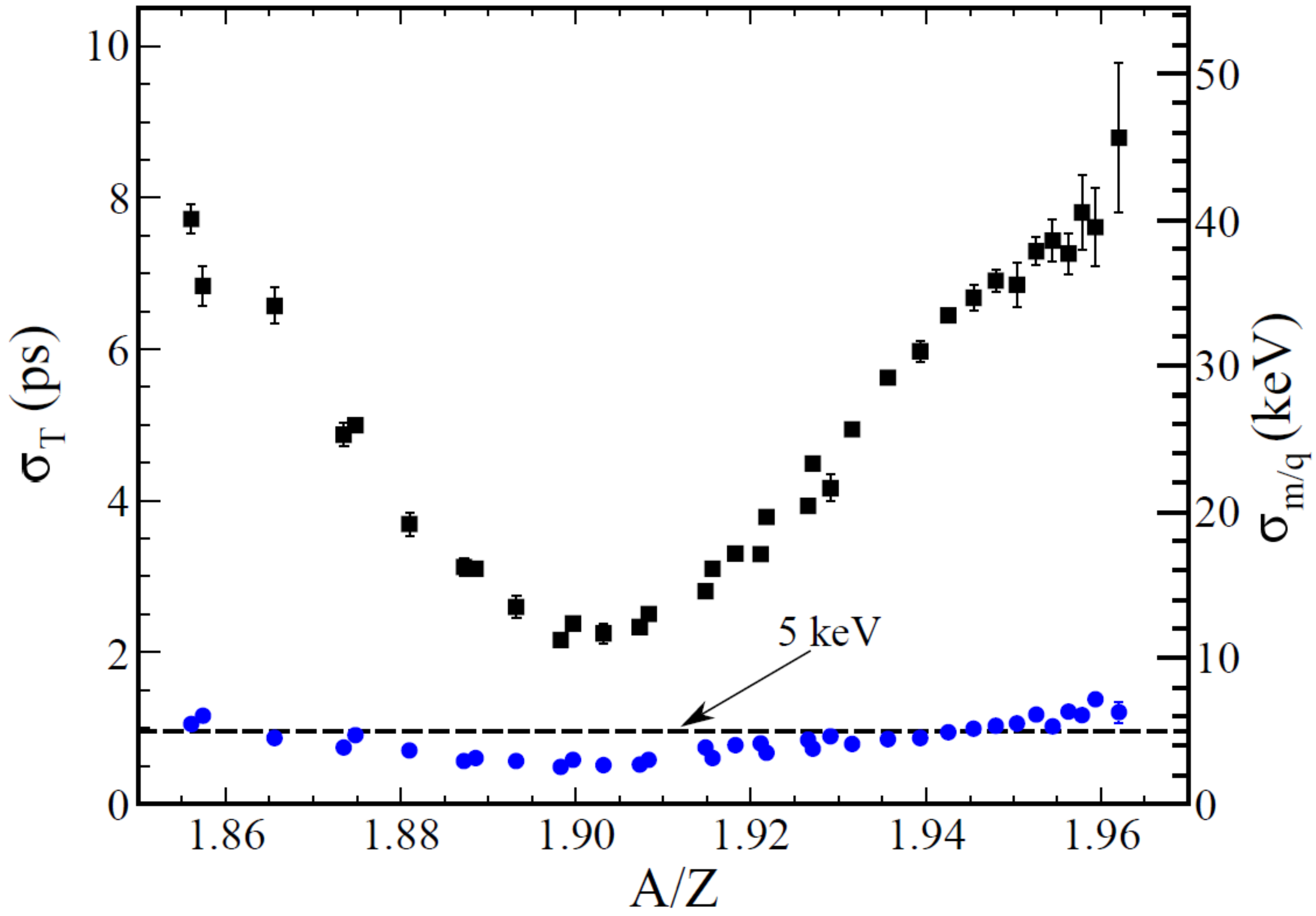
$$\frac{1}{w_i} = \frac{[\sigma_{B\rho}(\gamma^i_{\mathrm{exp}}, \gamma^i_t)]^2}{[f(C^i_{\mathrm{exp}})]^2}$$

Bρ-defined isochronous mass spectrometry



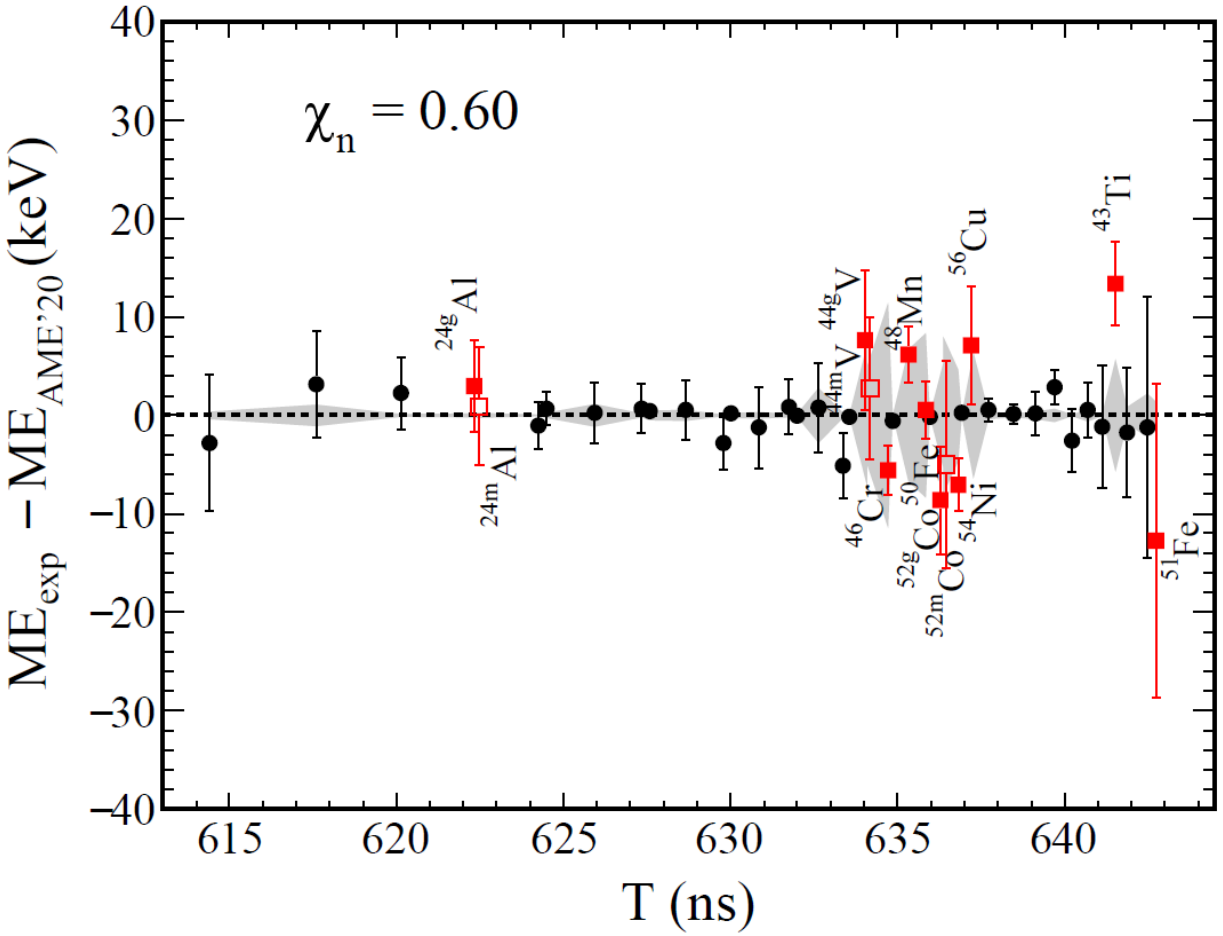
Bρ-defined isochronous mass spectrometry

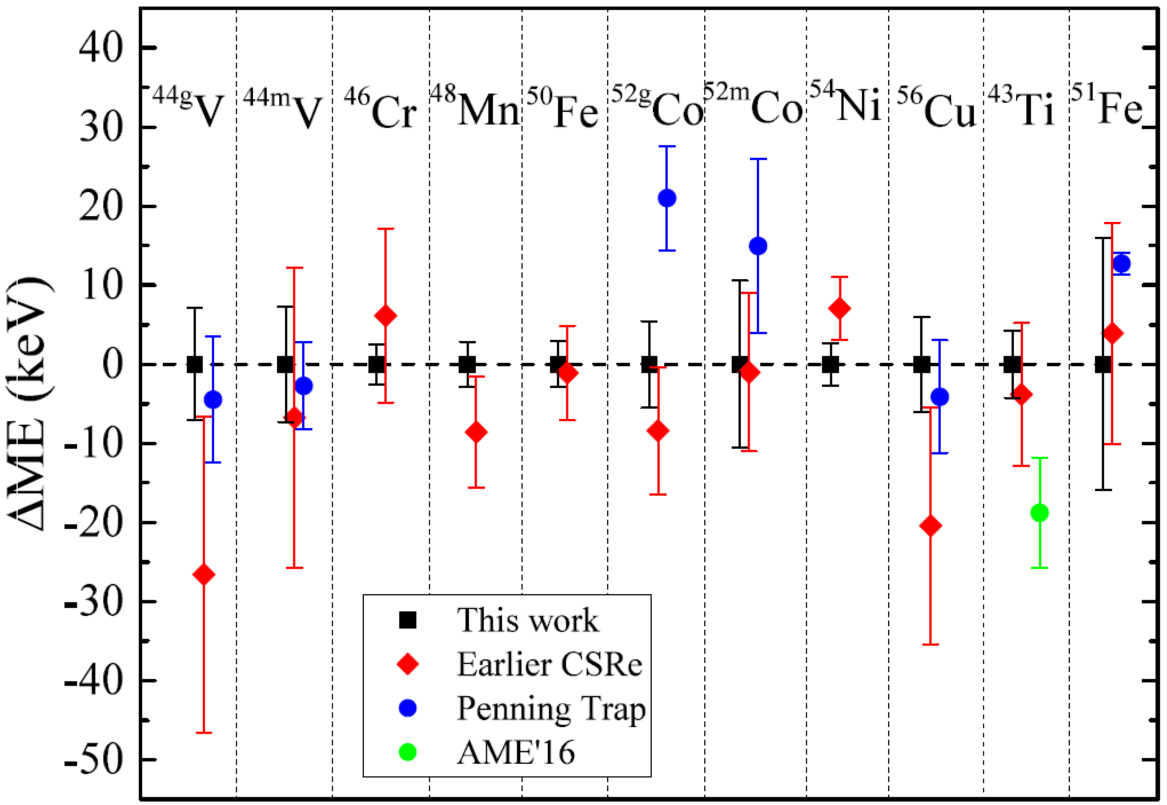




High precision broad-band measurements

Bρ-defined isochronous mass spectrometry





High precision broad-band measurements

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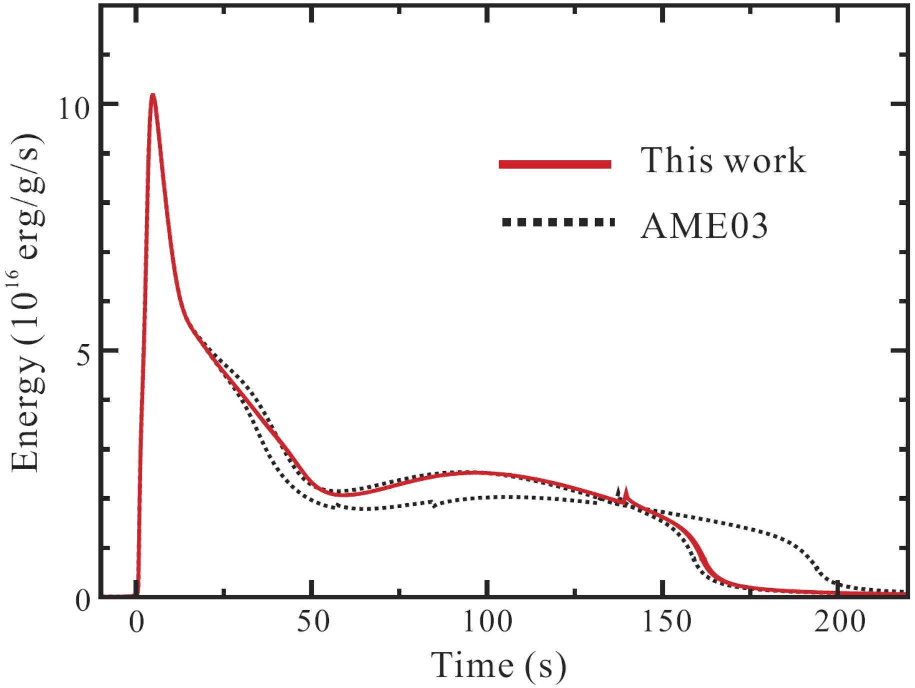
3. Bρ-defined isochronous mass spectrometry
4. New results and perspective

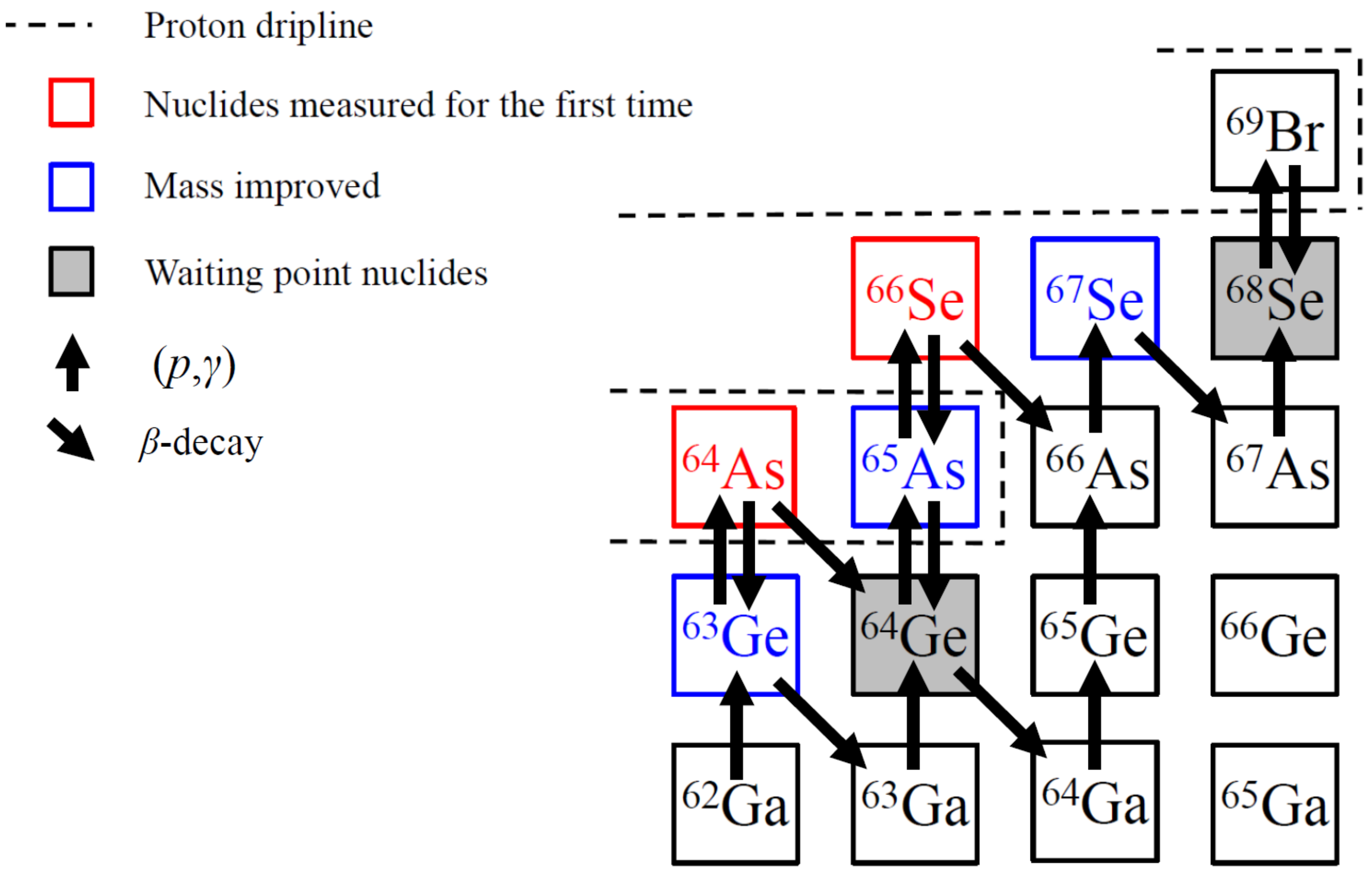
New mass results

PRL **106,** 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

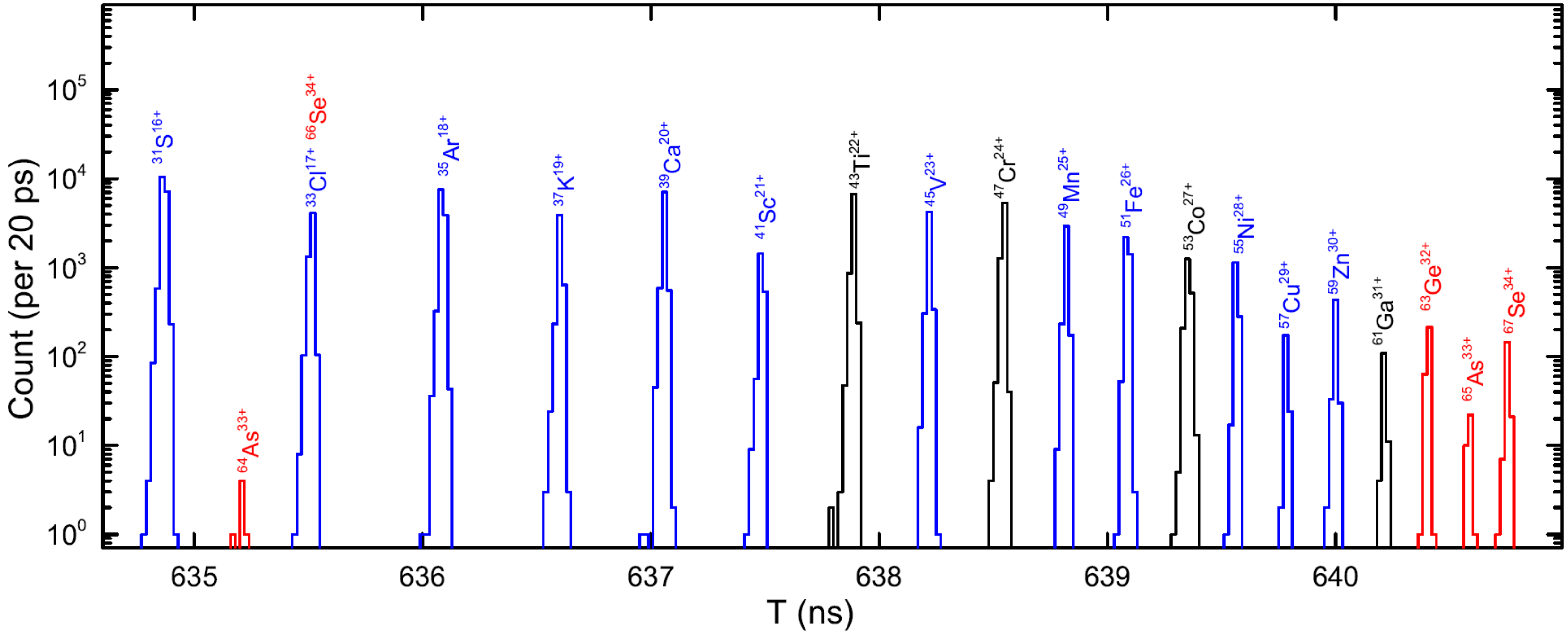
Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr and Their Impact on Nucleosynthesis in the *rp* Process

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wang,[1] Y. H. Zhang,[1] Yu. A. Litvinov,
J. W. Xia,[1] G. Audi,[7] K. Blaum,[3] C. M. Du,[1,2] P. Geng,[1,2] Z. G. Hu,[1] W

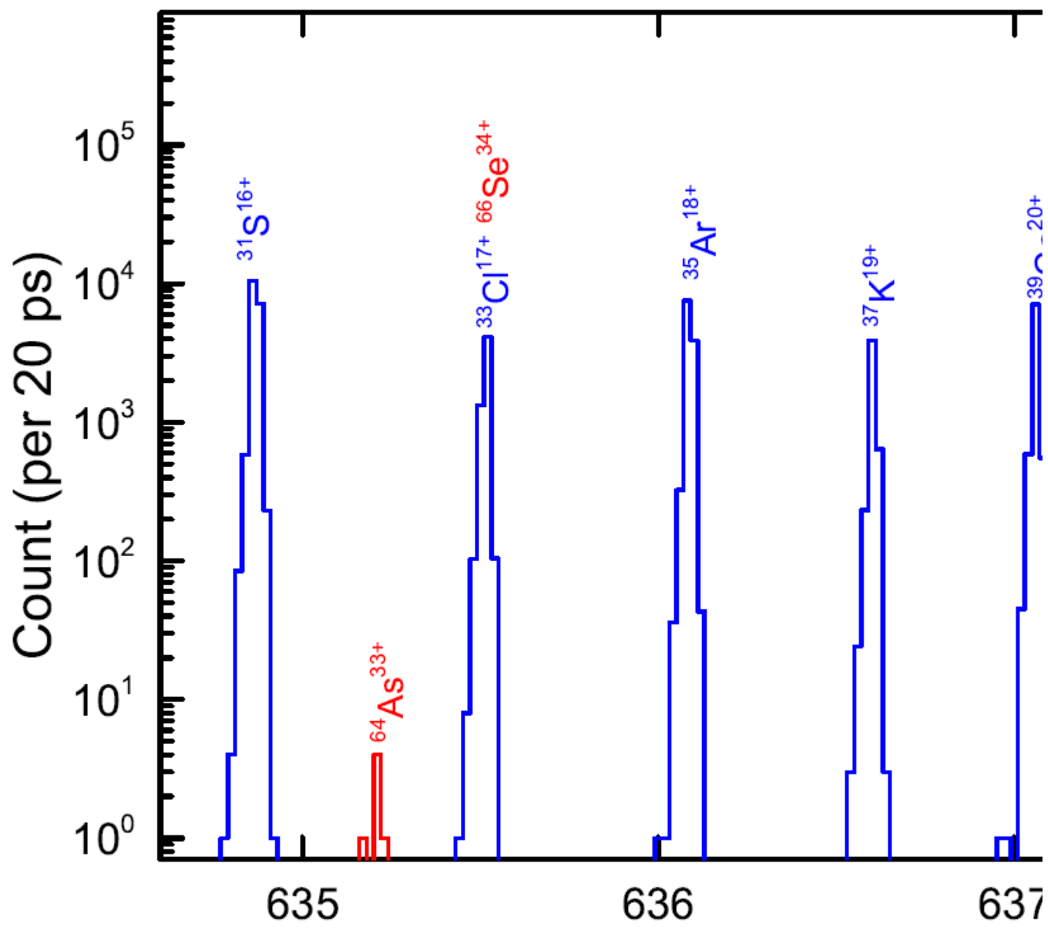


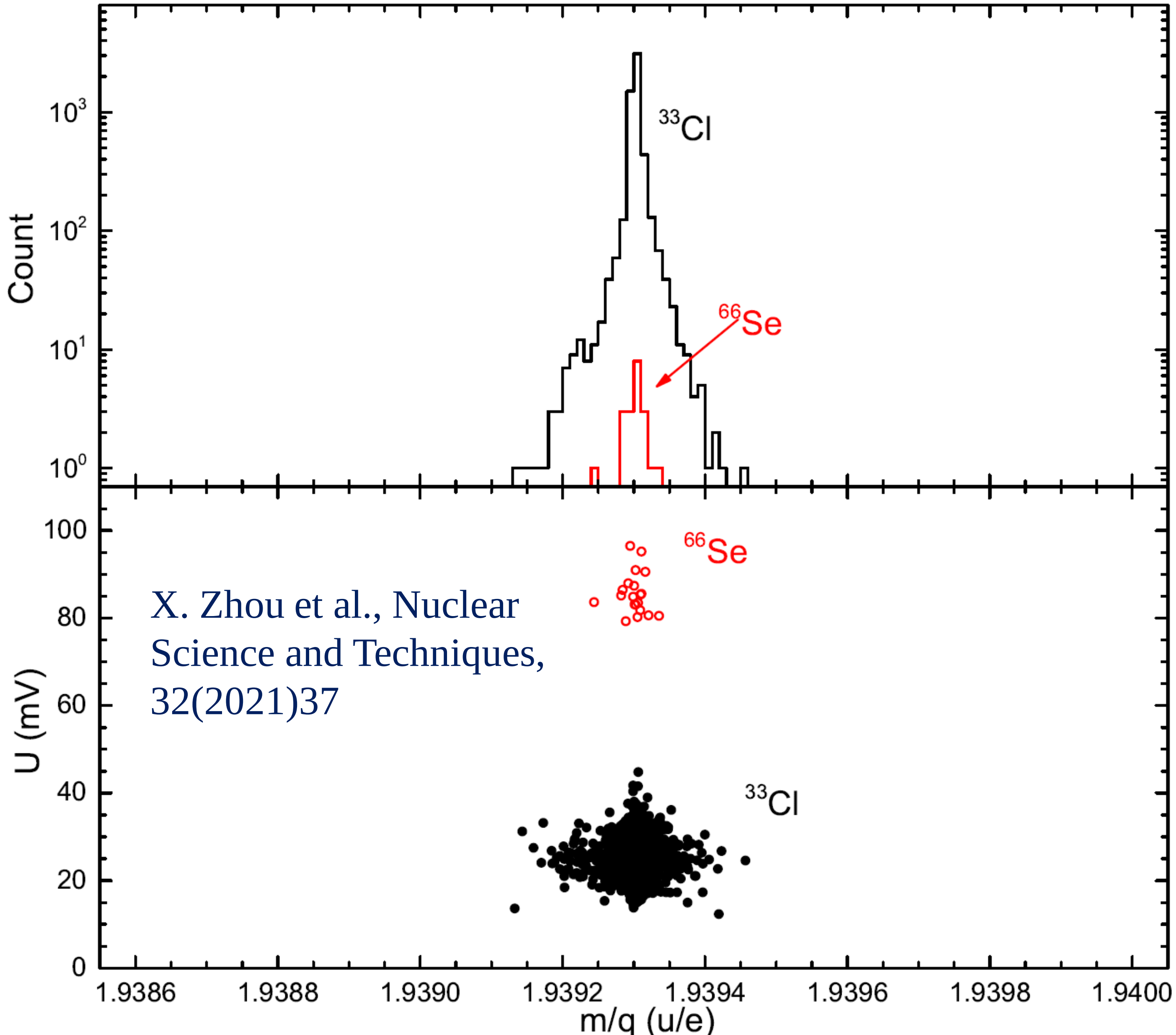


New mass results

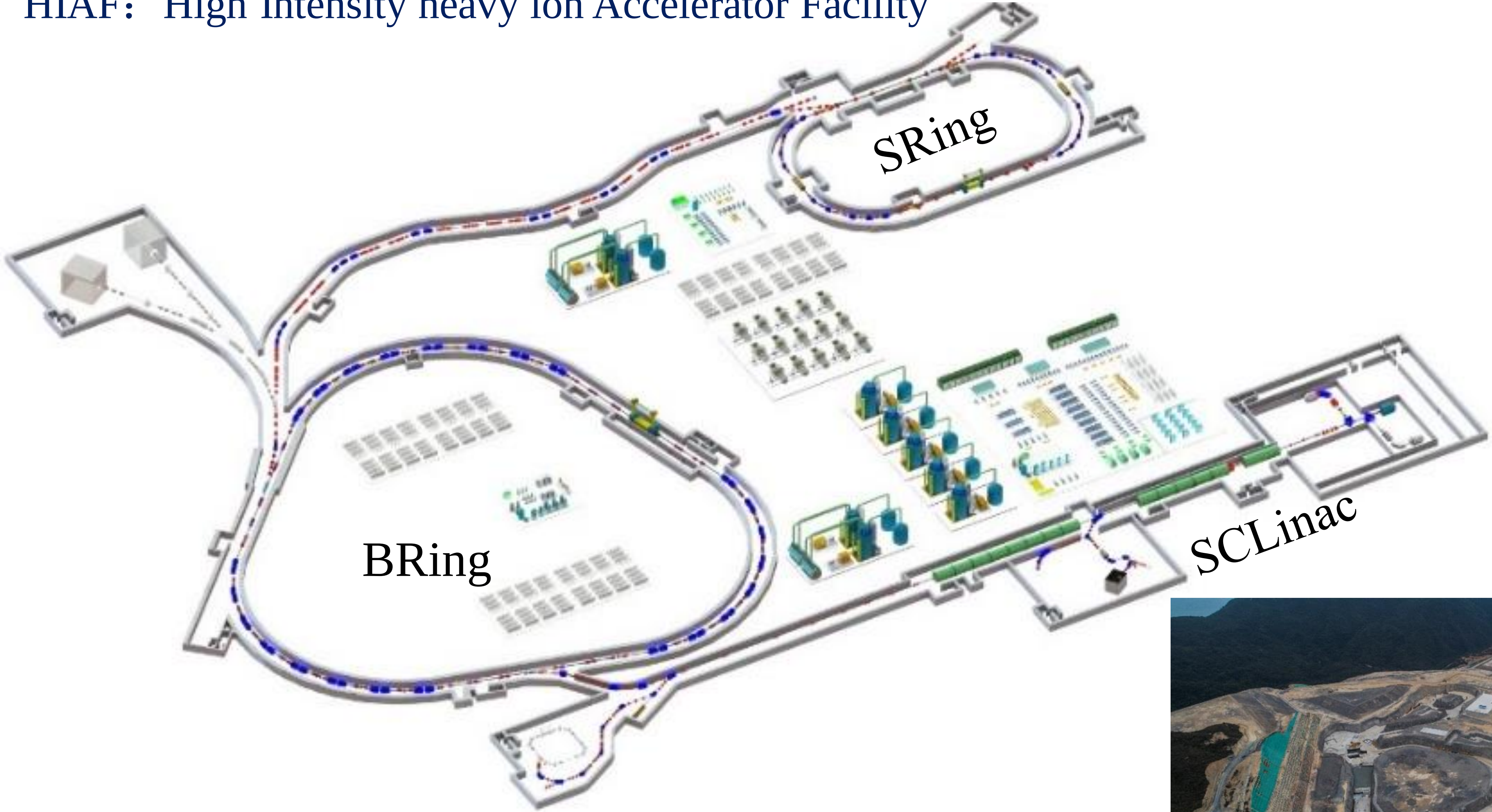


New mass results





HIAF：High Intensity heavy ion Accelerator Facility



Summary

1) Isochronous Mass Spectrometry have been used to measure short-lived nuclides at CSR to study issues in nuclear astrophysics and nuclear structure.
2) We have developed Bρ-defined IMS, which is a new tool for precision mass measurements of short-lived nuclei.
3) Owing to simultaneous measurement of the revolution time and velocity of every stored short-lived ion, the sensitivity and precision of the mass measurements were significantly increased.
4) The new research facility HIAF is being constructed and will provide new opportunities for nuclear physics.

Thank you for your attention !

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